NASA Advanced Modeling and Simulation Seminar

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UQ Analysis of DNS data with RANS-DNS simulations

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In collaboration with

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NASA Ames

NASA NNX12AJ61A

My background

Education

Ph. D. **Fluid & Plasma Mechanics**
M. S. **Physics**, Focus area: **Aerophysics & Gas Dynamics**

Affiliations

2010 - present	**University of New Mexico**: Mechanical Engineering
2003 – 2010	**Florida State University**: School of Computational Science Center for Advanced Power
2001 – 2003	**Texas A&M University**: Aerospace Engineering
1999 – 2001	**Stanford University:** Center for Turbulence Research
1996 – 1999	**Institute of Theoretical & Applied Mechanics**, Russia
1989 – 1993	**Institute of Thermophysics**, Russia

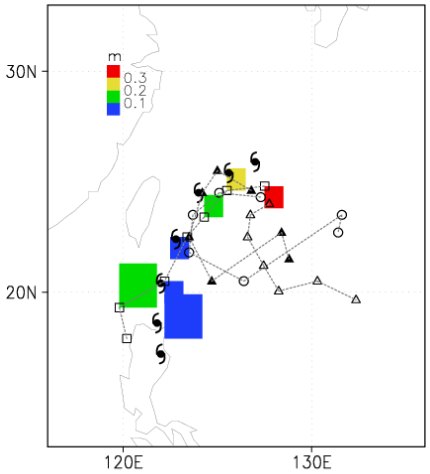
Research Interests

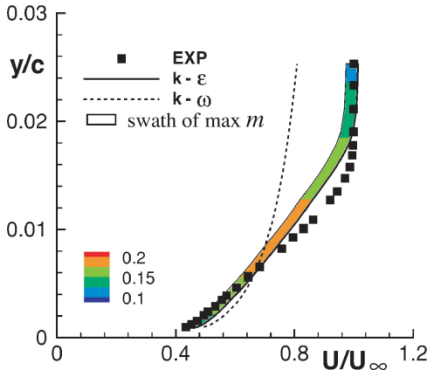
- Turbulence modeling for aerodynamic flows: statistical closures, DNS
- Analysis of simulation uncertainty:
  RANS-DNS simulations, evidence theory-based multi-model predictions
- Biomimetic rotor design for small rotorcrafts
- Alternative wind energy harvesting
- Survivability of networks

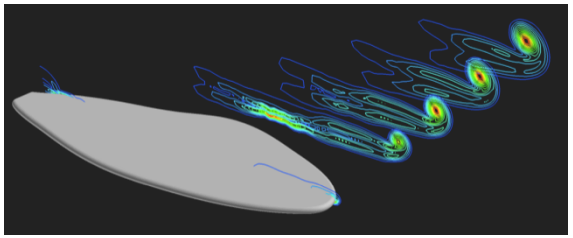
My background

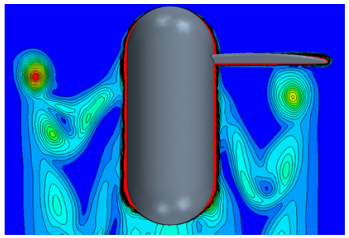
Research Areas

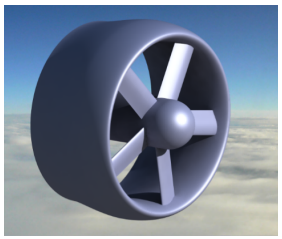
- **Turbulence modeling**: RANS, DNS
- **Analysis of simulation uncertainty**: RANS-DNS simulations, evidence theory
- **Multi-model predictions** evidence theory
- **Rotor design for small rotorcrafts**
- **Non-rotary wind energy harvesting**
- **Survivability of networks**: analysis and biomimetic design for power systems

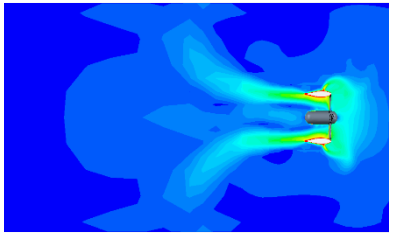












Motivation

- **Turbulence modeling: RANS**

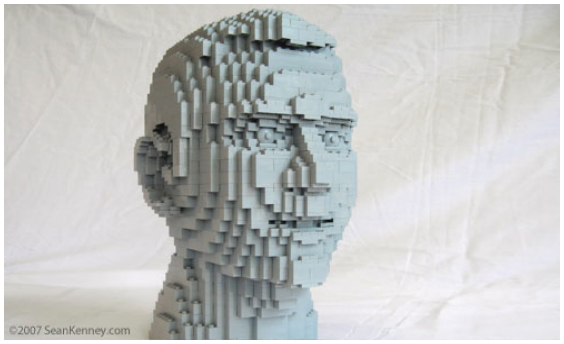
NNX12AJ61A goal:

to develop an accurate physics-based general framework capable of accurate modeling a wide range of aerodynamic turbulent flows without wall functions and with a minimum number of unknown coefficients

Possible solution: Fourth-order RANS (FORANS) closures

Justification

- The turbulent flow field representation by statistical moments is equivalent to the PDF representation.
- There is a direct connection between the number of equations solved and the amount of physics involved.
- Assumptions about PDF can be introduced in > 3rd-order closures.
- A FORANS model can possibly be reduced to a simpler model without wall-functions and unknown coefficients.



http://www.seankenney.com/portfolio/the_accomplished_man/

(Photo: jeshko) Youtube/jeshko

FORANS closures

$$\frac{\bar{D}U_i}{Dt} = -\frac{\partial < u_i u_j >}{\partial x_j} + \cdots$$

Standard models

$$\frac{\bar{D} < u_i u_j >}{Dt} = -\frac{\partial < u_i u_j u_k >}{\partial x_k} + \Pi_{ij} - \varepsilon_{ij} + \cdots$$

$$\frac{\bar{D} < u_i u_j u_k >}{Dt} = -\frac{\partial < u_i u_j u_k u_l >}{\partial x_l} + \Pi_{ijk} - \varepsilon_{ijk} + \cdots$$

$$\frac{\bar{D} < u_i u_j u_k u_l >}{Dt} = -\frac{\partial < u_i u_j u_k u_l u_m >}{\partial x_m} + \Pi_{ijkl} - \varepsilon_{ijkl} + \cdots$$

FORANS

Turbulent diffusion — **Truncated Gram-Charlier series expansions**

Velocity-pressure gradient correlations — **Data-driven model**

Dissipation — **DNS data**

Truncated Gram-Charlier series expansions:

$$< u^5 >= 10 < u^2 >< u^3 >$$

$$< v^5 >= 10 < v^2 >< v^3 >$$

$$< u^4 v >= 6 < u^2 >< u^2 v > +4 < u^3 >< uv >$$

$$< uv^4 >= 6 < v^2 >< uv^2 > +4 < v^3 >< uv >$$

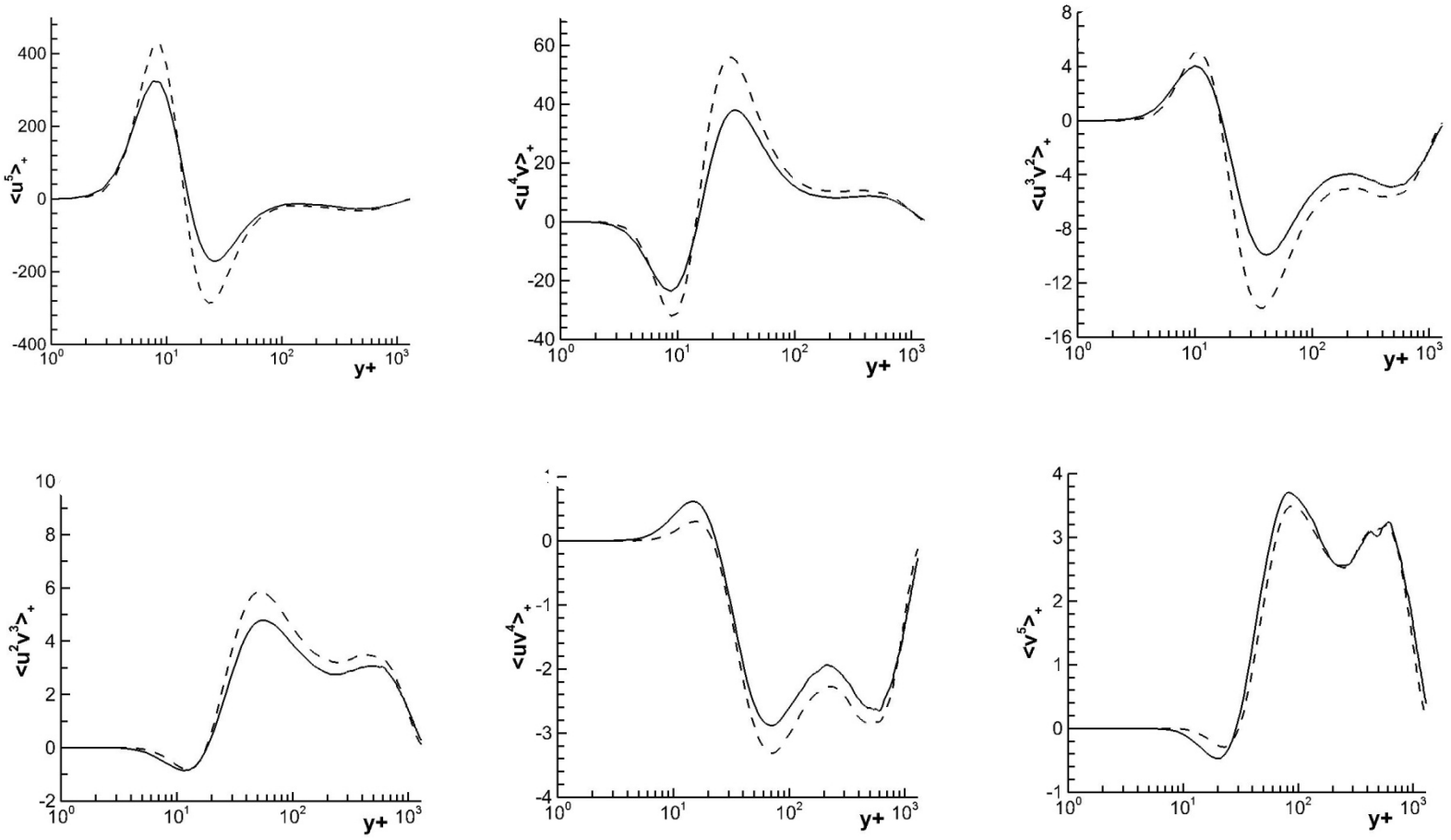
$$< u^2 v^3 >= 6 < uv >< uv^2 > + < u^2 >< v^3 > +3 < u^2 v >< v^2 >$$

$$< u^3 v^2 >= 6 < uv >< u^2 v > + < u^3 >< v^2 > +3 < uv^2 >< u^2 >$$

Kampé de Fériet (1966)
Durst et al. (BL, 1992)

Validation results: ZPG BL

Re_θ = 4101, 5200

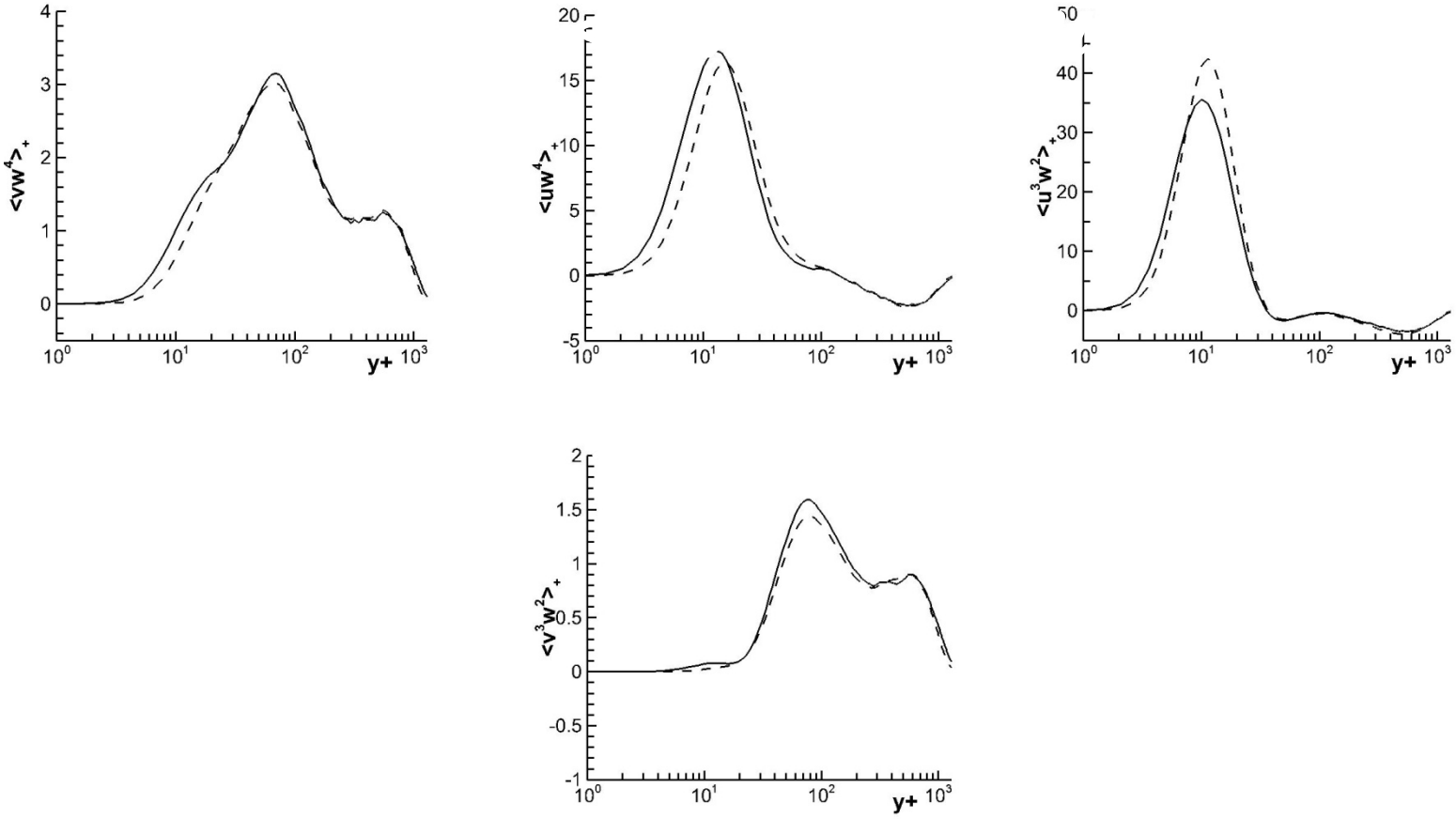


DNS Gram-Charlier representation using DNS data

Poroseva et al., Int. J. Heat Fluid Flow, 2015

DNS validation: ZPG BL

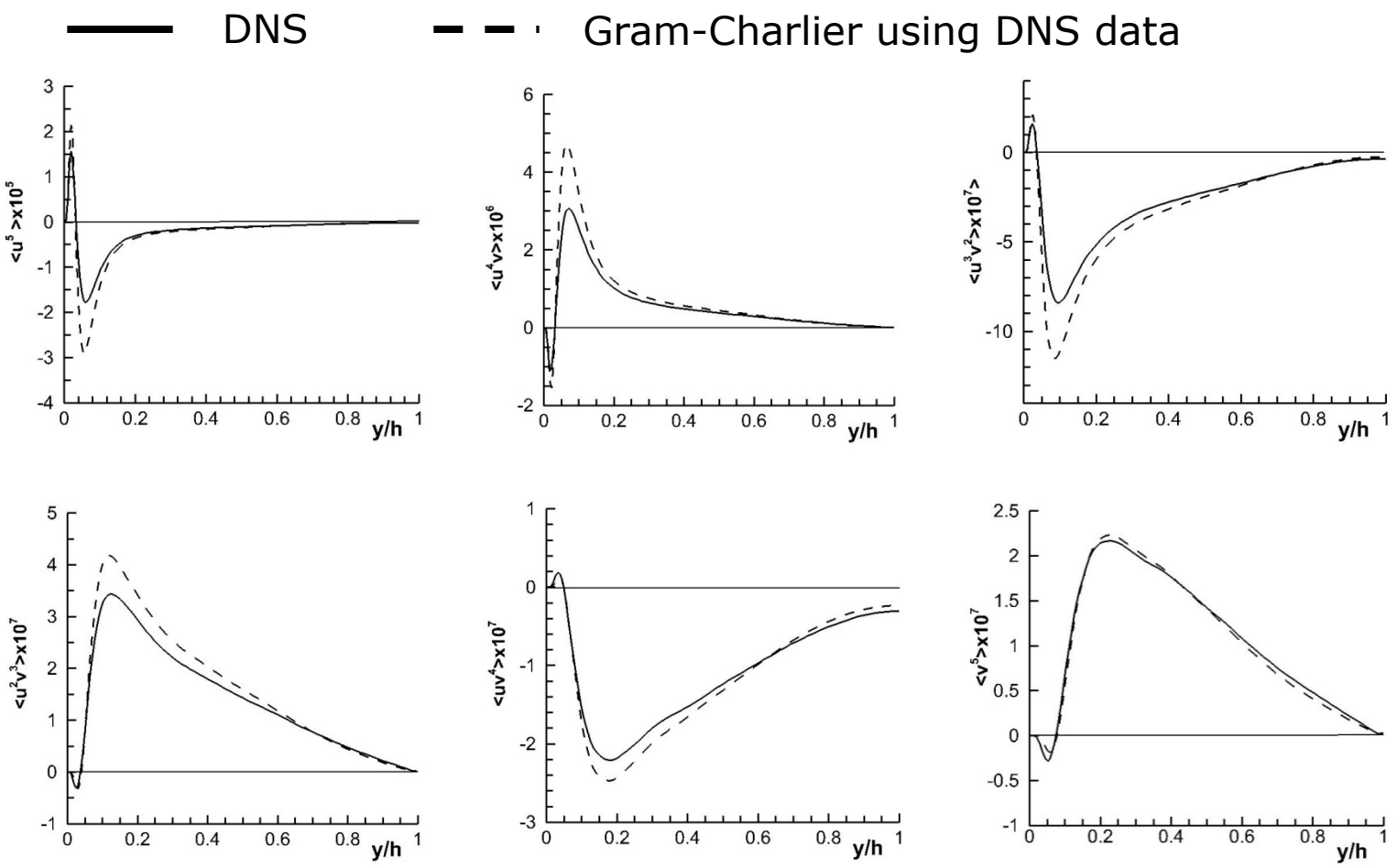
DNS Gram-Charlier using DNS data



Poroseva et al., Int. J. Heat Fluid Flow, 2015

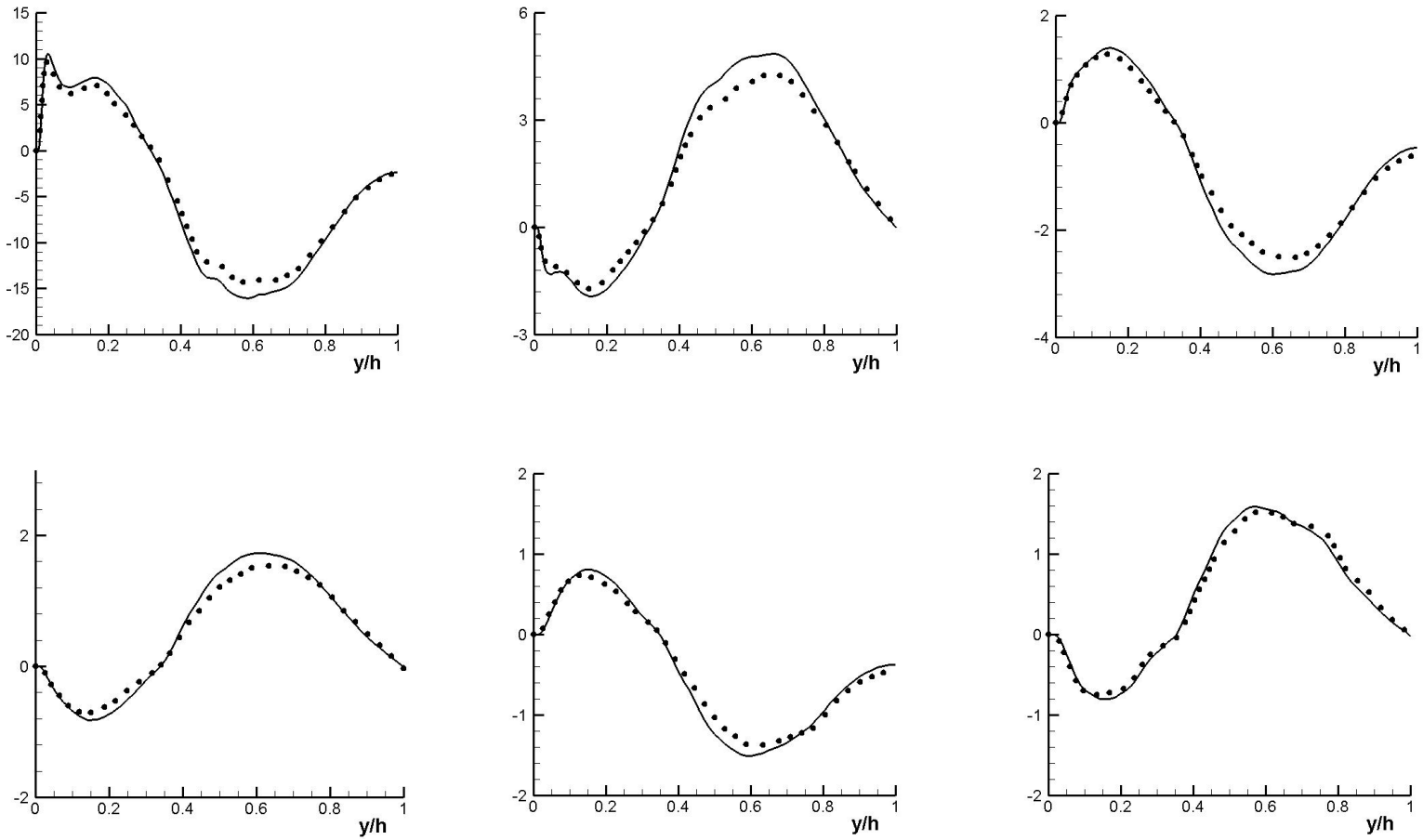
DNS validation: channel flow

Re_τ = 392



http://turbmodels.larc.nasa.gov/Other_DNS_Data/high-order-channel.html

Strained Channel: $A_{22}t = 0.772$



••• DNS ——— Gram-Charlier representation using DNS data

http://turbmodels.larc.nasa.gov/Other_DNS_Data/high-order-channel.html

Data-driven velocity/pressure-gradient models (planar flows, v.2)

$$\Pi_{xy} = -0.92 D^{T}_{xy} - 0.92 P_{xy} - 0.3 D^{M}_{xy}$$

$$\Pi_{xx} = -0.78 \Pi_{xy} - 0.7 \Pi_{yy} - 0.25 D^{T}_{xy} + 0.01 D^{M}_{xx}$$

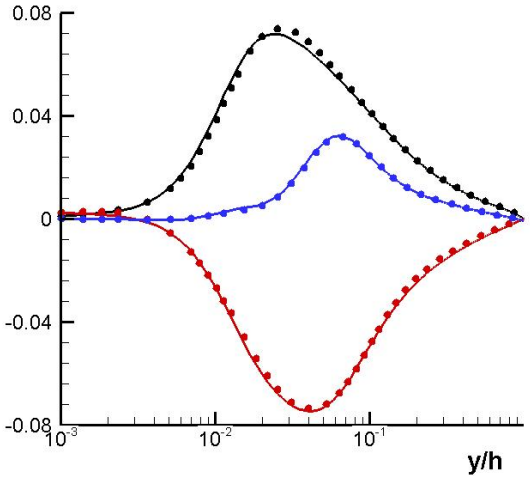
$$\Pi_{yy} = -0.45 P_{xy} - 0.031 P_{xx} - 1.35 D^{T}_{yy} + 1.15 D^{T}_{zz} - 0.47 D^{T}_{xy} + 0.2 D^{M}_{yy}$$

Poroseva et al., AIAA2015-3067

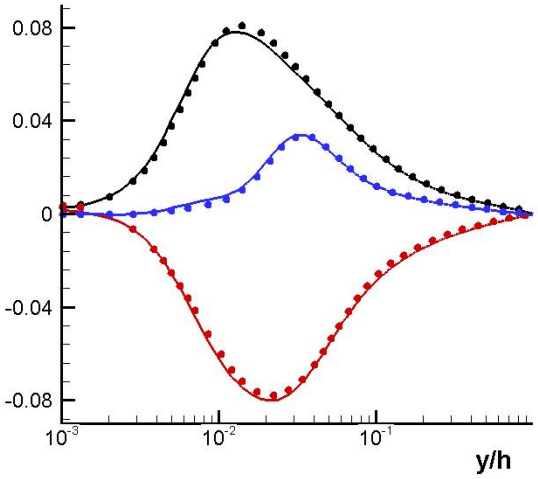
Poroseva & Murman, Proc. TSFP-9, TSFP-10

Fully-developed channel

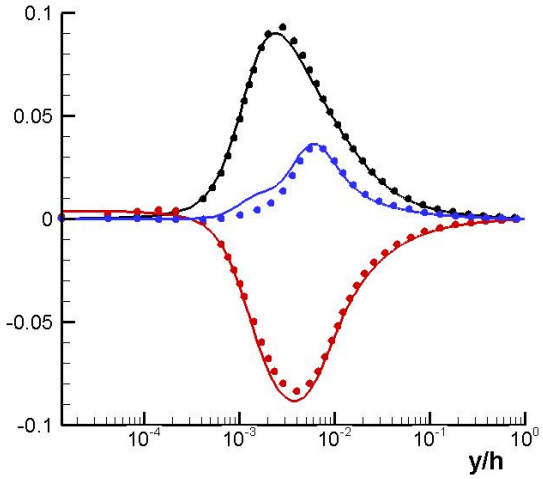
Re_τ = 550



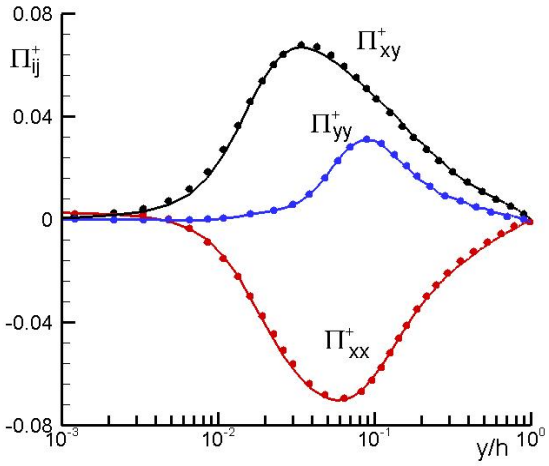
Re_τ = 1000



Re_τ = 5200



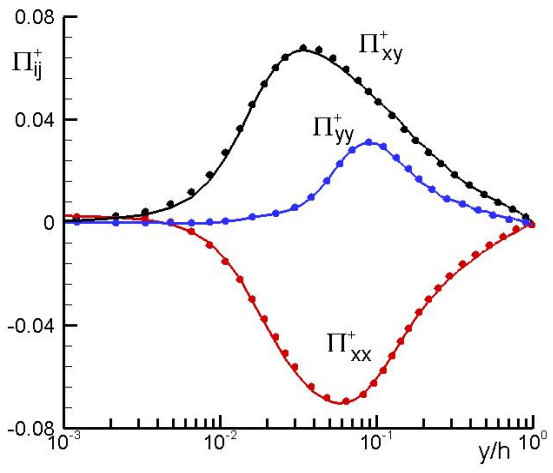
Lee & Moser, JFM, 2015



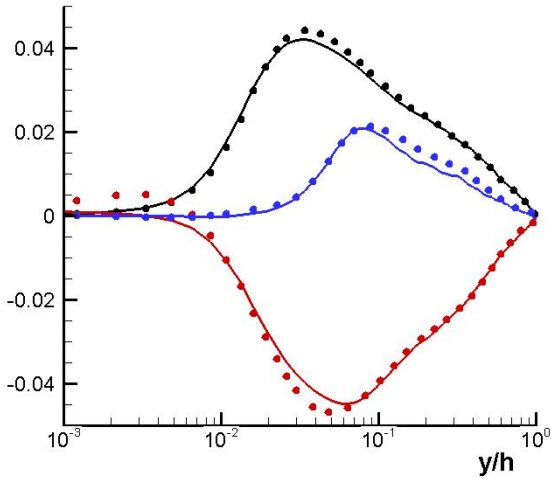
Re_τ = 395

Jeyapaul et al., AIAA2014-2088

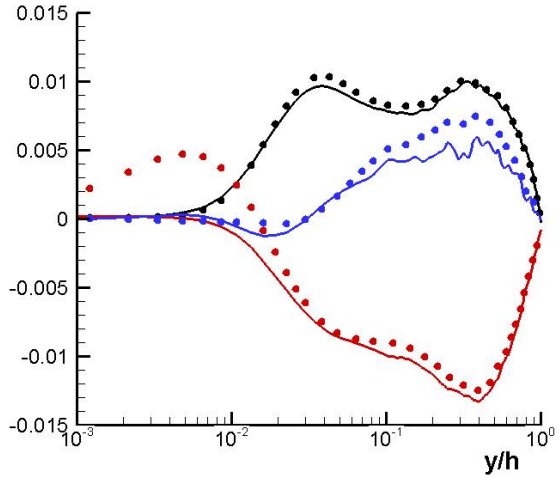
Strained channel/ZPG BL



$A_{22}t = 0$



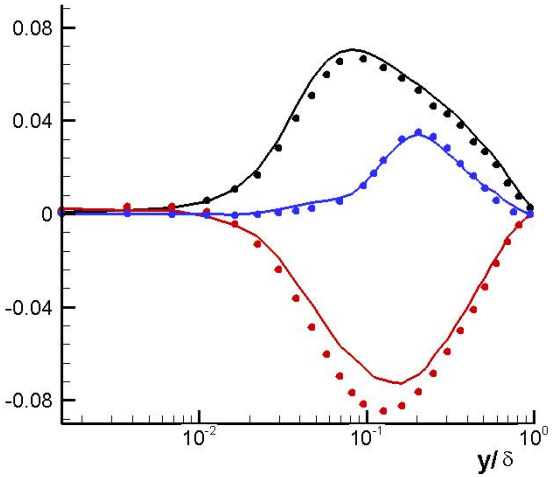
$A_{22}t = 0.281$



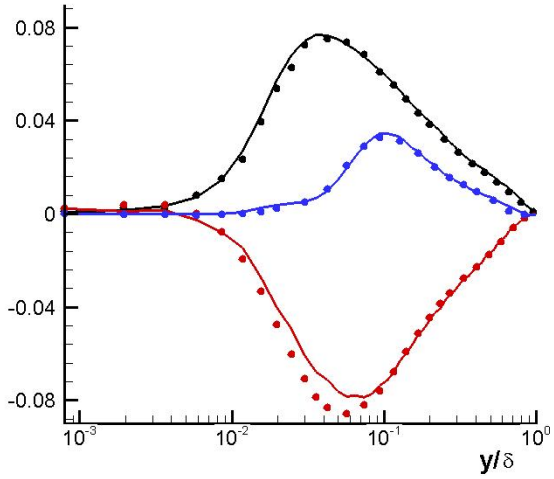
$A_{22}t = 0.772$

http://turbmodels.larc.nasa.gov/Other_DNS_Data/high-order-channel.html

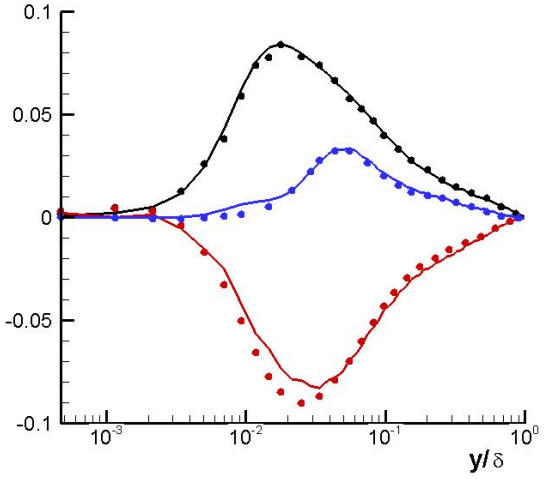
Re_τ = 300



Re_τ = 670



Re_τ = 1410

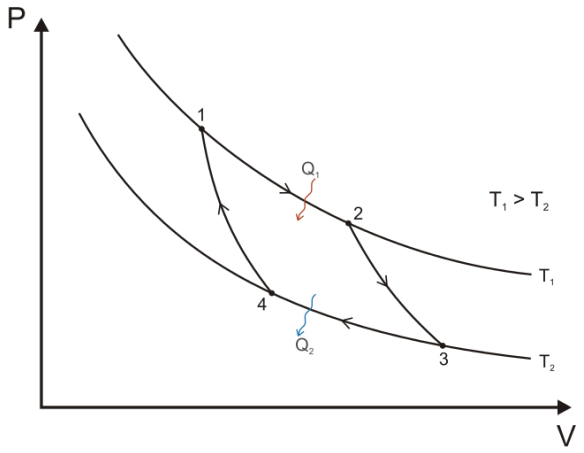


Spalart, JFM, 1988

Why cannot one obtain the accurate solution of the RANS equations with very accurate models for their terms?

What is the limit for physics-based RANS models?

Because we cannot have 100% efficient engine…sort of…



"Ideal" RANS model

$$\frac{\bar{D} < u_i u_j u_k u_l >}{Dt} = D^M_{ijkl} + D^T_{ijkl} + P_{ijkl} + P^T{}_{ijkl} + \Pi_{ijkl} - \varepsilon_{ijkl}$$

$$\frac{\bar{D} < u_i u_j u_k >}{Dt} = D^M_{ijk} + D^T_{ijk} + P_{ijk} + P^T{}_{ijk} + \Pi_{ijk} - \varepsilon_{ijk}$$

$$\frac{\bar{D} < u_i u_j >}{Dt} = D^M_{ij} + D^T_{ij} + P_{ij} + \Pi_{ij} - \varepsilon_{ij}$$

$$\frac{\bar{D} U_i}{Dt} = \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial < u_i u_j >}{\partial x_j}$$

Data from direct numerical simulations

This is the definition of RANS-DNS simulations

- Framework should be applicable to any flow simulations
- A type of differential equations should be preserved
- A same solver should be used as in simulations with a model

Poroseva et al., AIAA2015-3067

Poroseva & Murman, Proc. TSFP-9, 2015

Numerical procedure

Test flows:

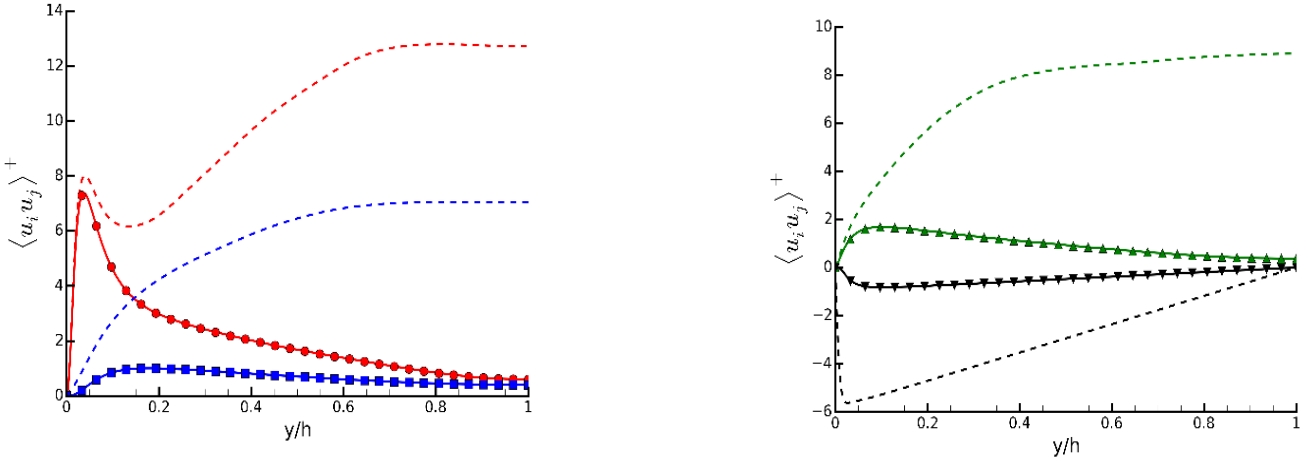
- a fully-developed channel flow at the DNS flow conditions
  Lee & Moser, 2015
  Jeyapaul et al. 2015

- zero-pressure gradient boundary layer over a flat plate
  Sillero et al., 2013

Solvers: OpenFOAM and in-house code for fully-developed flows

Grids: from DNS + grid sensitivity analysis

"Ideal" model (RANS-DNS) results



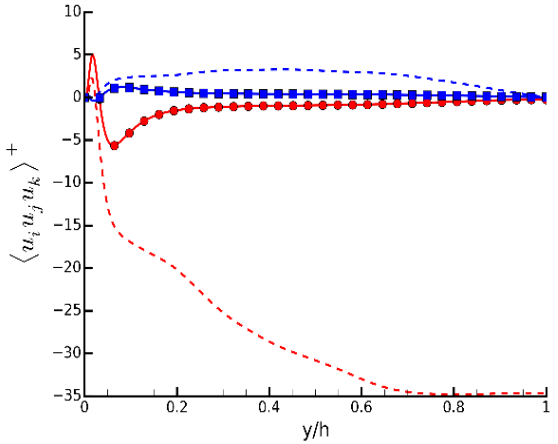
DNS data: • $< u^2 >$, ■ $< v^2 >$, ▲ $< w^2 >$, ▼ $< uv >$, RANS-DNS - - -

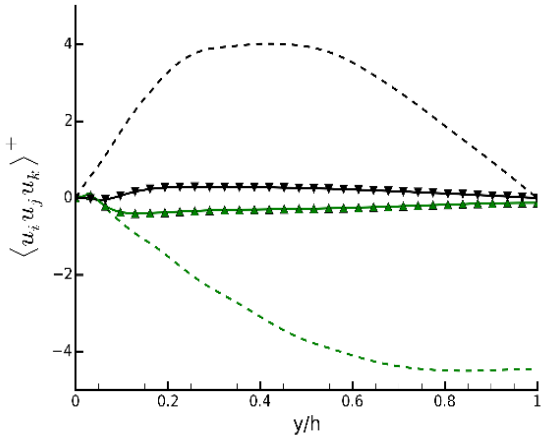
Jeyapaul et al. 2015

Re_τ = 395

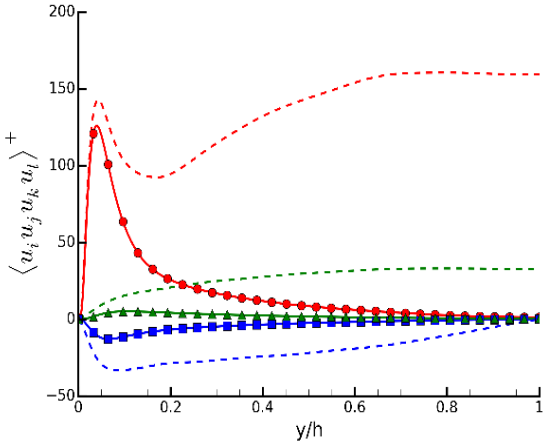
Symbols: DNS data
Dashed lines: RANS-DNS simulations

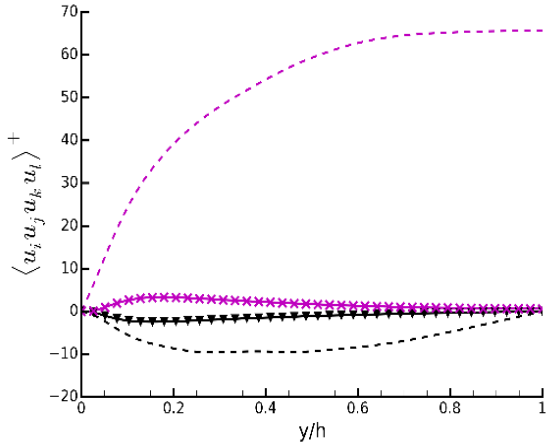
RANS-DNS results





DNS data: • $< u^3 >$, ■ $< u^2 v >$, ▲ $< uv^2 >$,▼ $< v^3 >$, RANS-DNS - - -



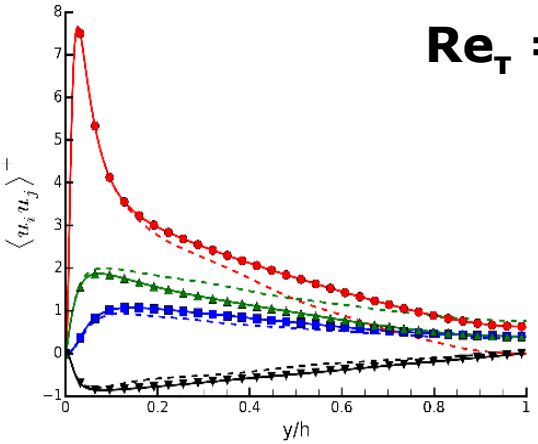


DNS data: • $< u^4 >$, ■ $< u^3 v >$, ▲ $< u^2 v^2 >$,▼$< uv^3 >$, x $< v^4 >$, RANS-DNS - - -

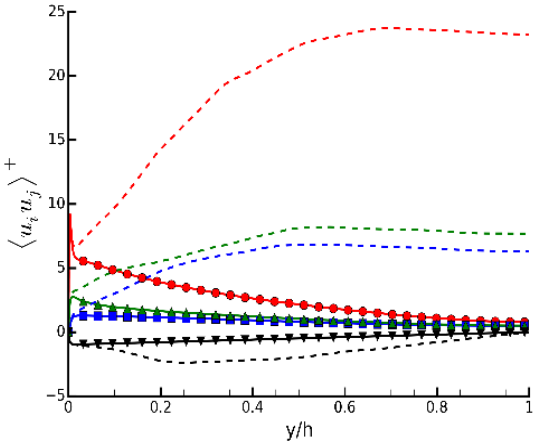
RANS-DNS results

Similar results were obtained with different database
(Lee & Moser, JFM, 2015)

Re_τ = 550



and at different Reynolds number: Re_τ = 5200



DNS data: • $< u^2 >$, ■ $< v^2 >$, ▲ $< w^2 >$,▼ $< uv >$, RANS-DNS - - -

Uncertainty analysis

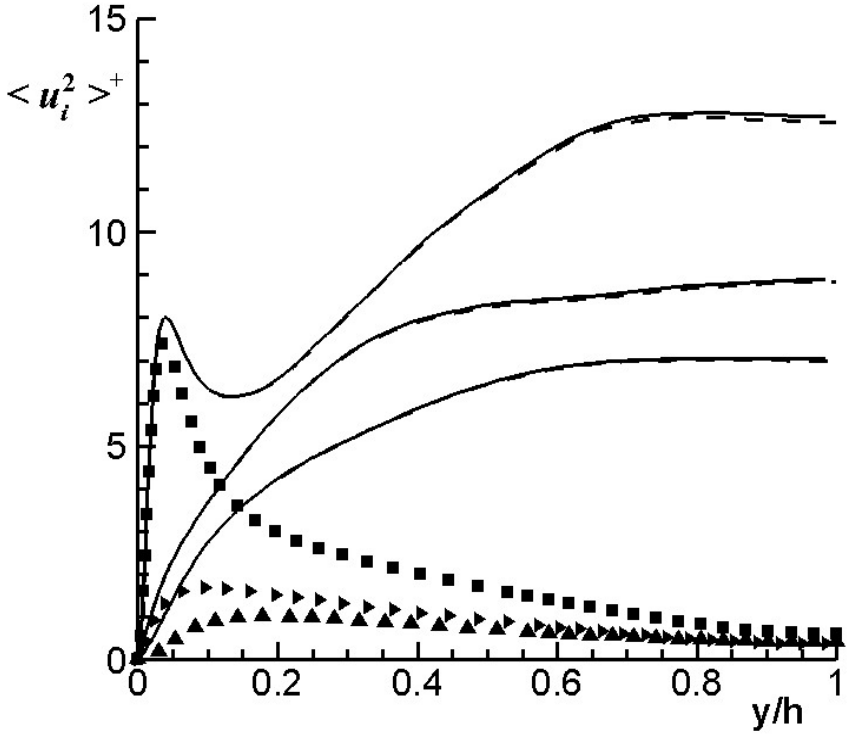
Solutions of the "ideal" model with no modeling involved are unphysical….

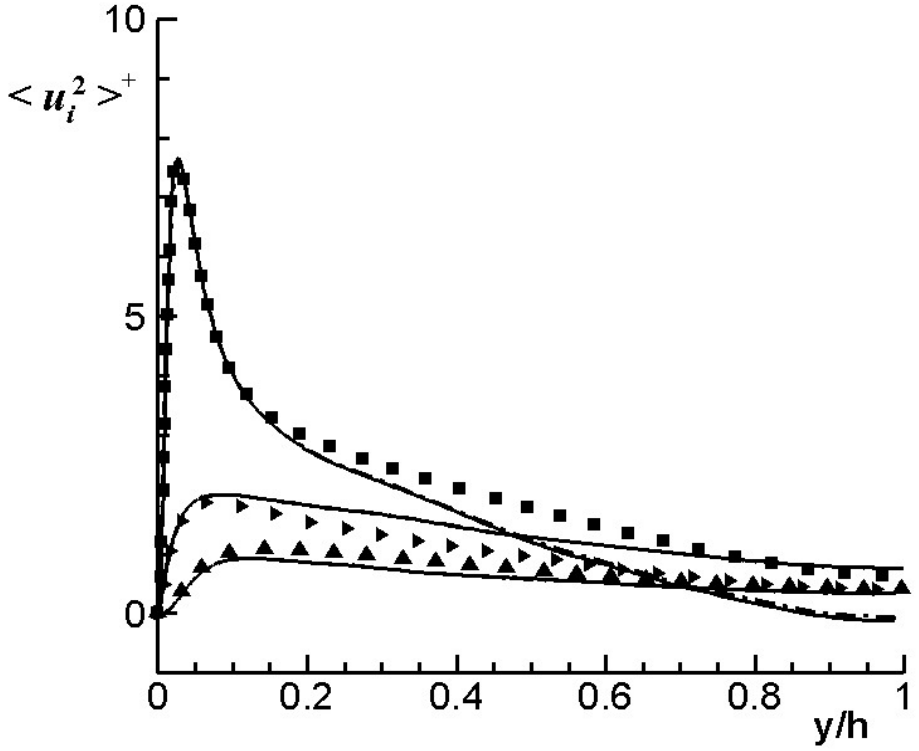
One cannot expect a physics-based turbulence model to outperform the solution based on DNS data….

Uncertainty sources in RANS-DNS simulations

- Numerical procedure used in RANS simulations
- DNS data
- Interaction of both

UQ analysis of RANS-DNS simulations





$$\mathrm{Re}_\tau = 550$$

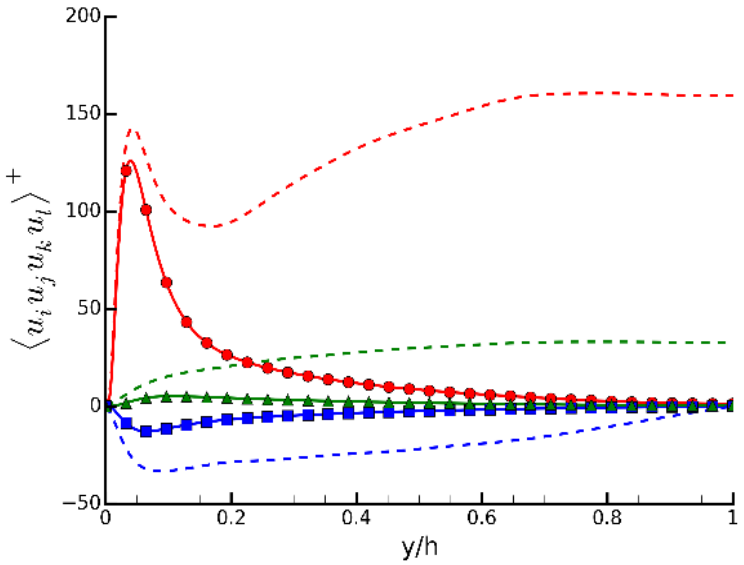
Different solvers

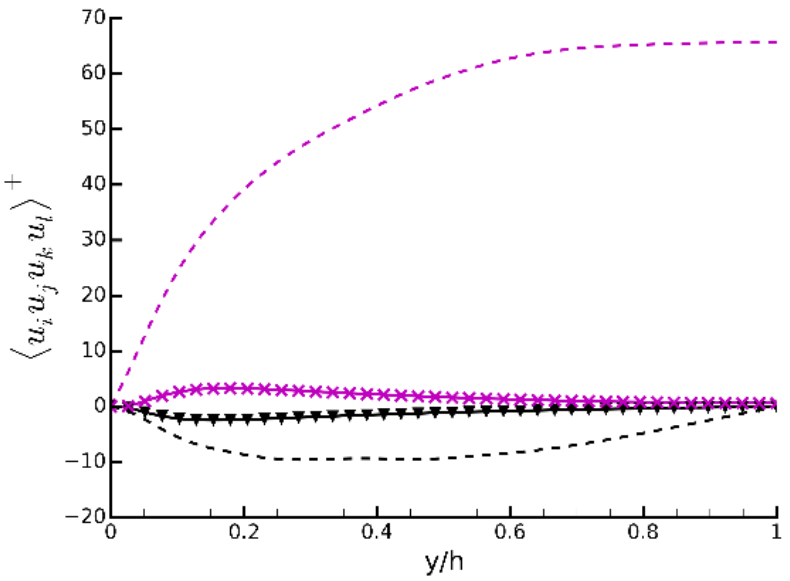
Different grids

Poroseva et al., Physics of Fluids, 2016

UQ analysis of RANS-DNS simulations

And this is due to inaccuracies of DNS data





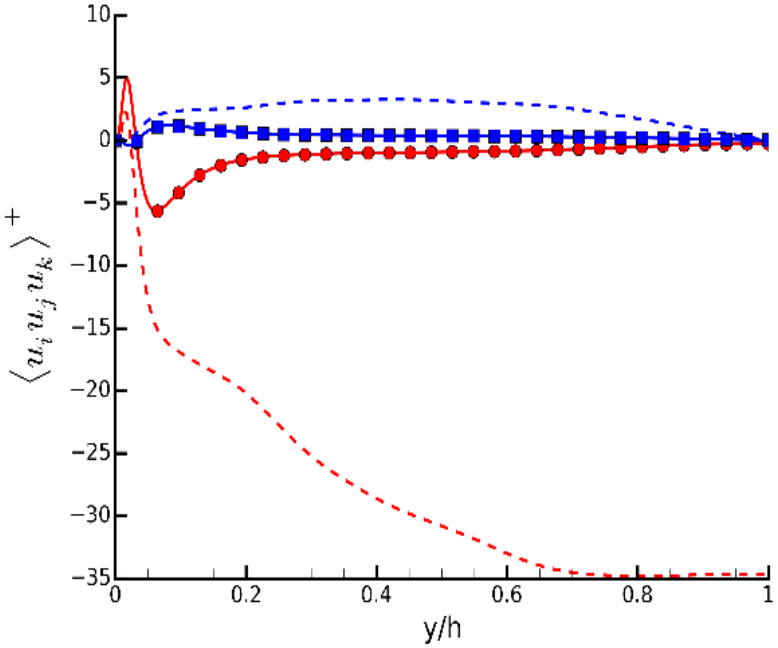
$$0 = D_{ij}^M + D_{ij}^T + P_{ij} + \Pi_{ij} - \varepsilon_{ij}$$

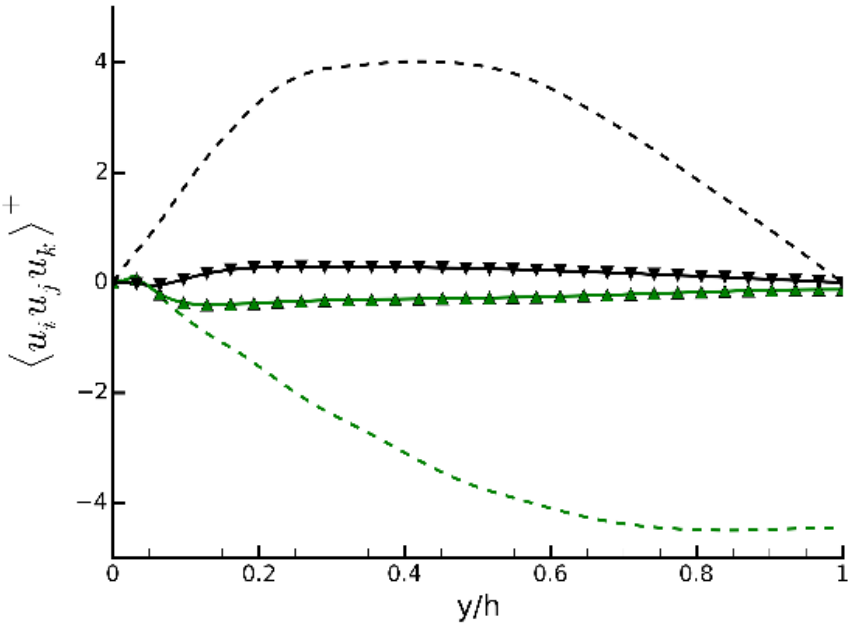
Dashed lines

$$0 = D_{ij}^M + D_{ij}^T + P_{ij} + \Pi_{ij} - \varepsilon_{ij} - Err_{ij}$$

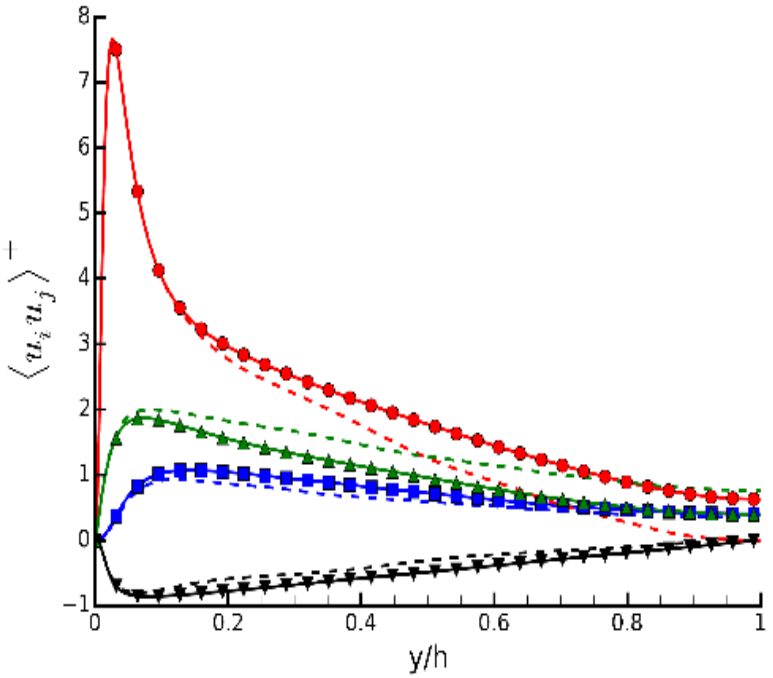
Solid lines

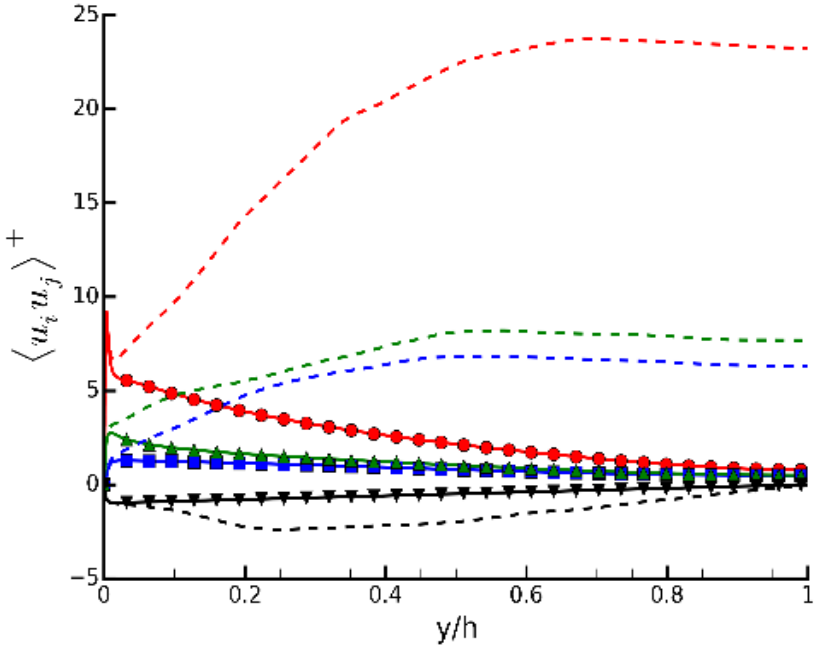
Re_T = 395





DNS data: • $< u^3 >$, ■ $< u^2 v >$ ▲ $< uv^2 >$ ▼ $< v^3 >$ RANS-DNS with error —





Re_τ = 550

Re_τ = 5200

DNS data: • $< u^2 >$, ■ $< v^2 >$, ▲ $< w^2 >$, ▼ $< uv >$, RANS-DNS with error —

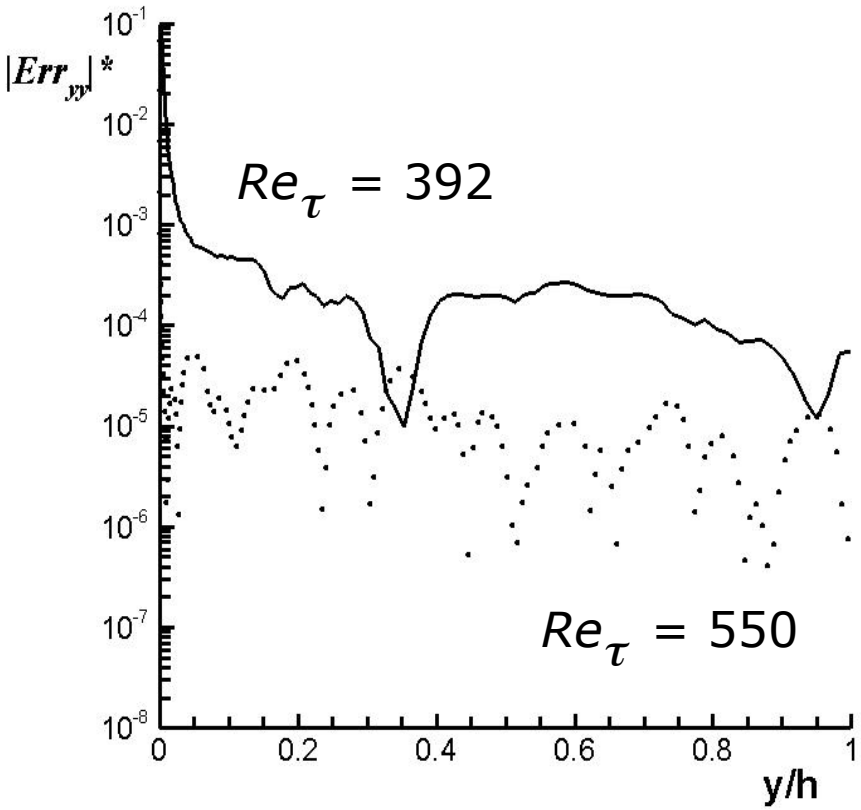
Uncertainties in DNS data are the current dominant source of uncertainties in RAND-DNS simulations.

How to deal with sensitivity of RANS equations for the modeling purposes is an open issue, but this sensitivity makes RANS-DNS simulations a convenient tool for the UQ analysis of DNS data.

S. V. Poroseva, J. D. Colmenares F., S. M. Murman, Physics of Fluids, 2016.

S. V. Poroseva, E. Jeyapaul, S. M. Murman, J. D. Colmenares F. AIAA2016-3940

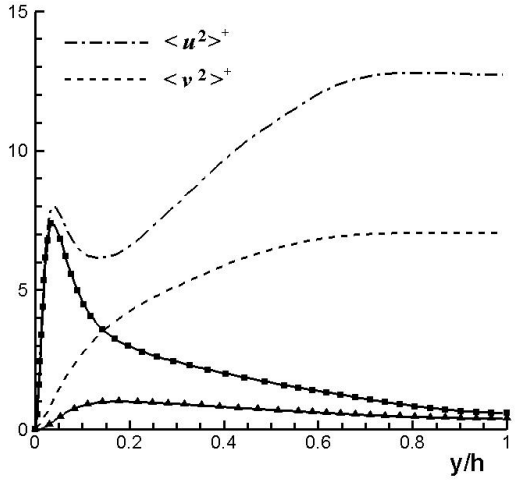
Uncertainty in DNS data (balance errors)



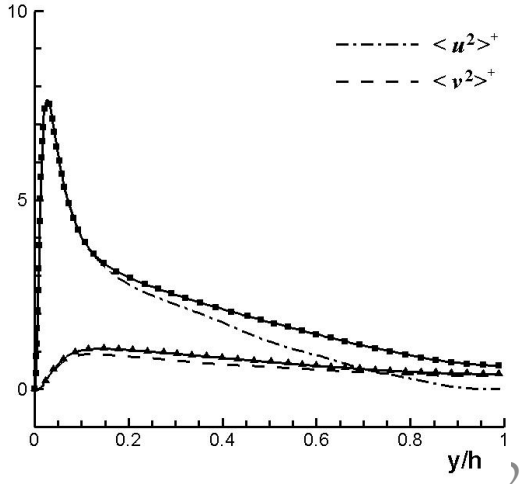
$$\left|Err_{yy}\right|^* = \left|Err_{yy}\right| / < v^2 >$$

Balance errors < 0.1% of $<u_i u_j>$

Jeyapaul et al., 2015 Re_τ = 392

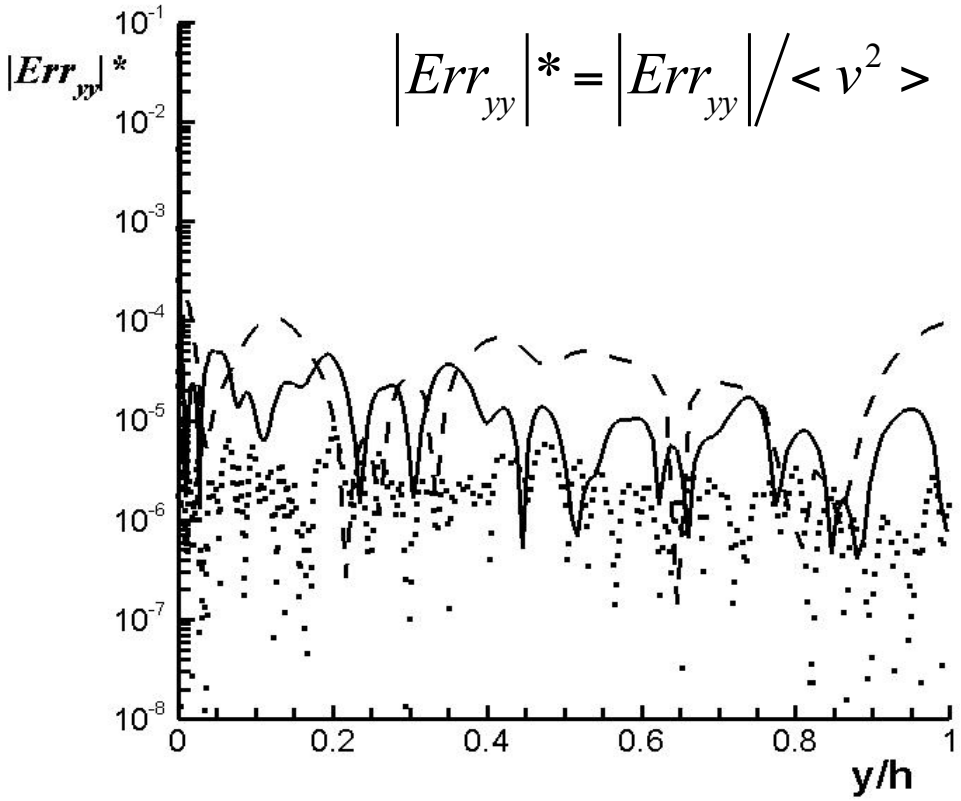


Lee & Moser, 2015 Re_τ = 550



Balance errors at different Re

$$\left|Err_{yy}\right|^{*} = \left|Err_{yy}\right| / \langle v^2 \rangle$$

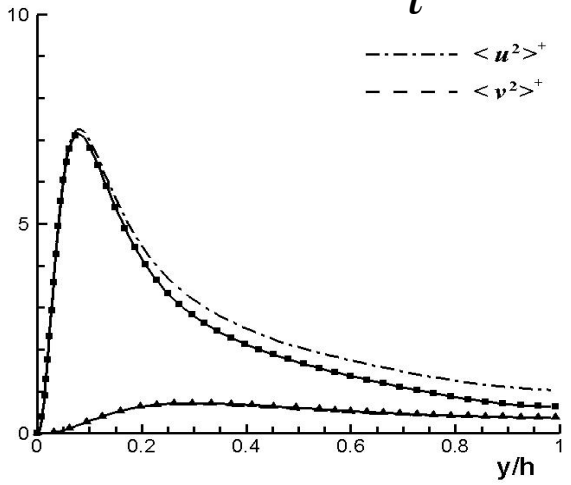


Re_τ = 5200 •••••

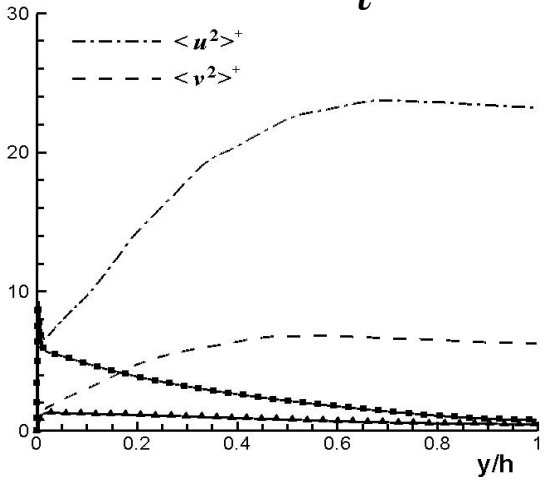
Re_τ = 550 ——

Re_τ = 180 - - -

Re_τ = 180



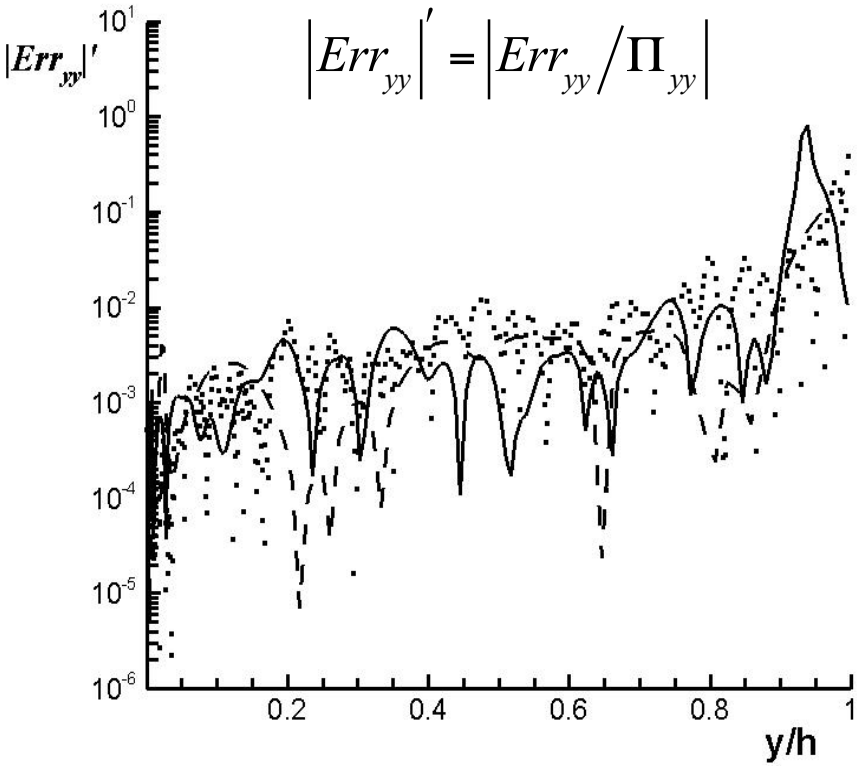
Re_τ = 5200

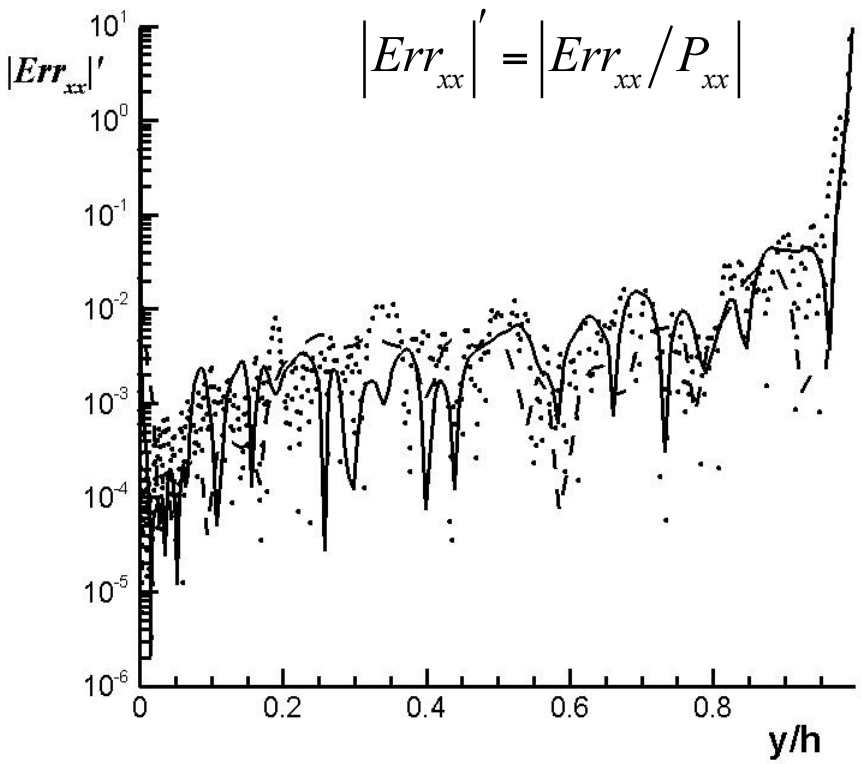


Lee & Moser, 2015

(Contd.)

Lee & Moser, 2015





Re_τ = 5200 •••••

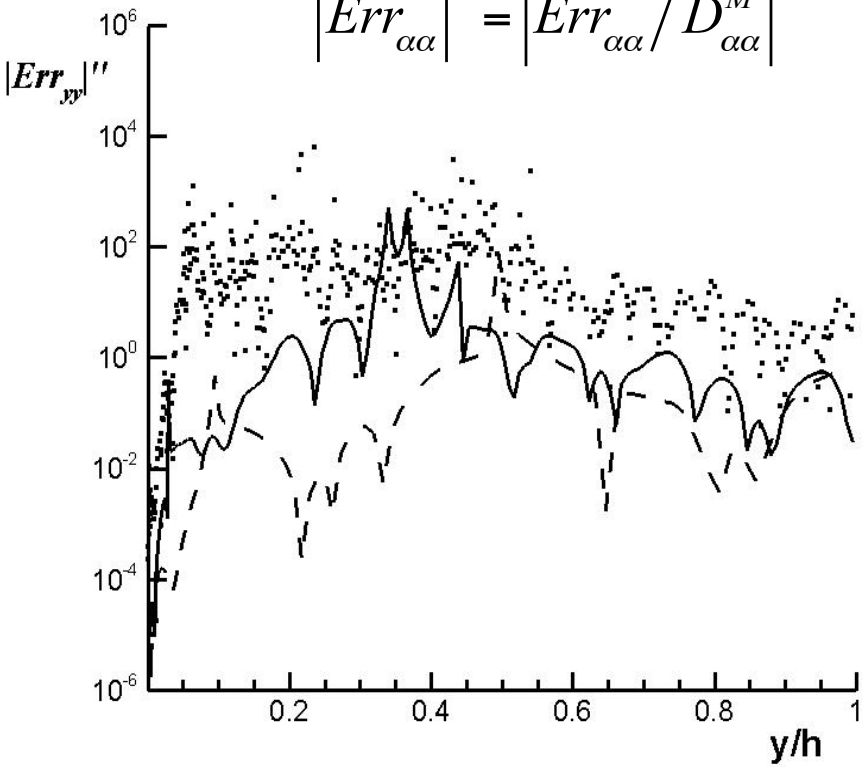
Re_τ = 550 ——

Re_τ = 180 - - -

Balance errors < 1% in such normalization with these data

Balance errors vs. viscous diffusion

$$\left|Err_{\alpha\alpha}\right|'' = \left|Err_{\alpha\alpha} / D^{M}_{\alpha\alpha}\right|$$



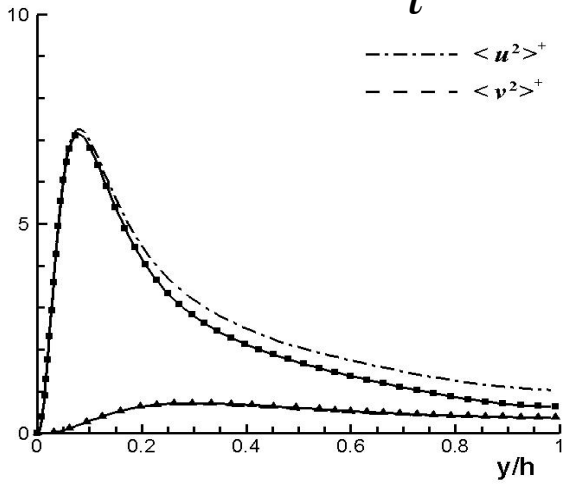
Re_τ = 5200 •••••

Re_τ = 550 ——

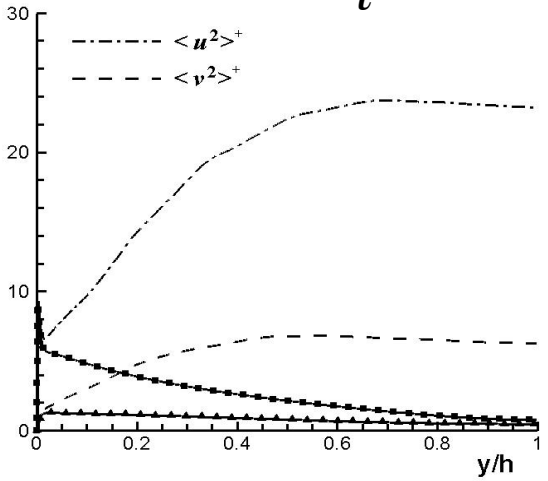
Re_τ = 180 - - -

Balance errors are huge….

Re_τ = 180



Re_τ = 5200



UQ metric for quantitative analysis

$$\Delta_{\max} = \frac{\left|g(y) - f(y)\right|_{\infty}}{\left|g(y)\right|_{\infty}}$$

based on L_∞-norm

$g(y)$ – DNS profile

$f(y)$ – RANS-DNS solution

Lee & Moser, 2015 **(in %)**

$\Delta_{\max}$	$< u^2 >$	$< v^2 >$	$< uv >$	$< w^2 >$
$Re_\tau = 180$	6	5	5	13
$Re_\tau = 550$	10	17	21	20
$Re_\tau = 5200$	287	548	173	308

(Contd.)

in %

	Δ_{max}	$< u^2 >$	$< v^2 >$	$< uv >$	$< w^2 >$
Lee & Moser, 2015	Re_τ = 550	10	17	21	20
Jeyapaul et al., 2015	Re_τ = 392	164	663	629	507

Jeyapaul et al., 2015

	$< u^2 >$	$< v^2 >$	$< uv >$	$< w^2 >$
Δ_{max}	164	663	629	507
	$< u^3 >$	$< v^3 >$	$< uv^2 >$	$< u^2v >$
Δ_{max}	625	1290	1170	243
	$< u^4 >$	$< v^4 >$	$< uv^3 >$	$< u^3v >$
Δ_{max}	125	1970	474	354

Contribution of the statistical error

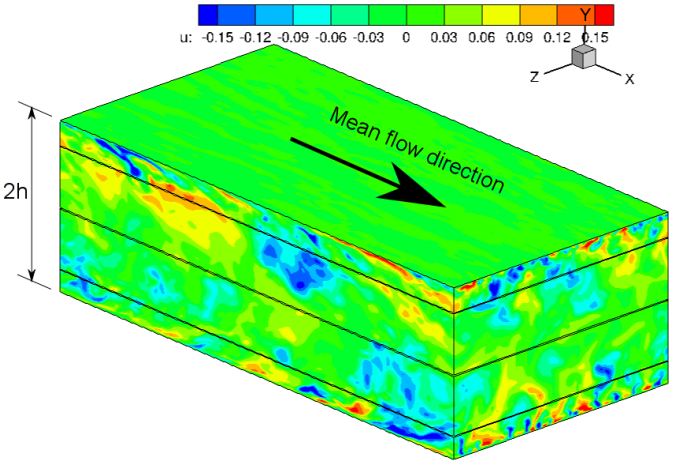
Poroseva et al., AIAA2016-3940

Test case: channel flow Re_τ = 392

DNS pseudo-spectral (Fourier/Chebyshev-τ) method

Coleman et al. 2003

2πh x 2h x πh



256x193x192
spectral modes

N	1	2	3	4	5	6	7
realizations	25	50	100	159	200	500	1000
t steps	4.72 X10^6	5.01 X10^6	5.51 X10^6	6.1 X10^6	6.51 X10^6	9.51 X10^6	14.69 X10^6

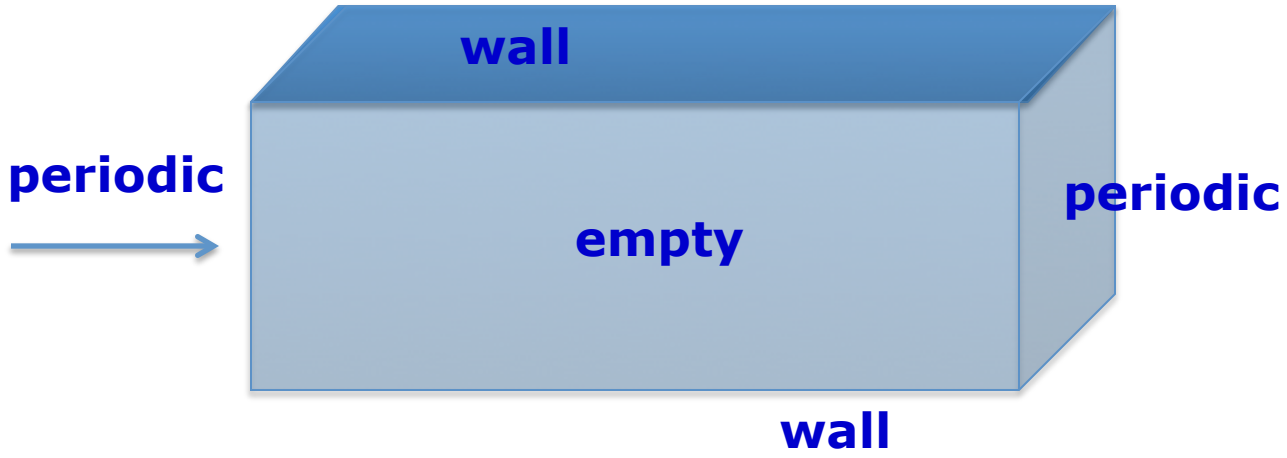
Jeyapaul et al., IJHFF, 2015

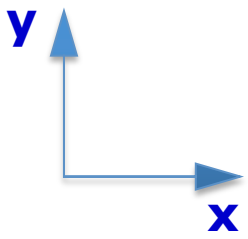
RANS-DNS simulations

Re_τ = 392

$$0 = D_{ij}^{M} + D_{ij}^{T} + P_{ij} + \Pi_{ij} - \varepsilon_{ij}$$

Sover: OpenFOAM

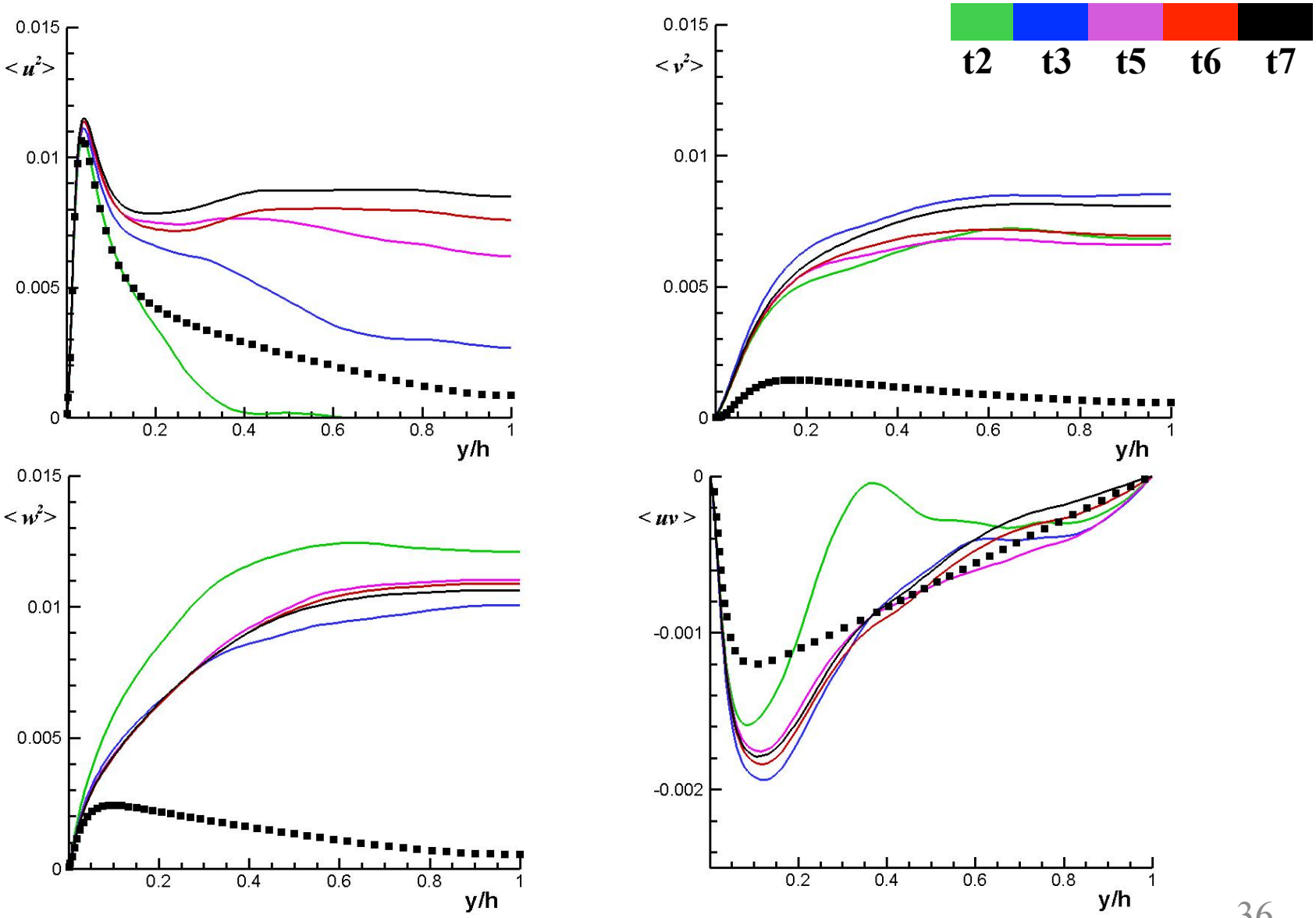




$Lx \times Ly \times Lz = 0.1h \times 2h \times 0.1h$

$Nx \times Ny \times Nz = 2 \times 193 \times 2$

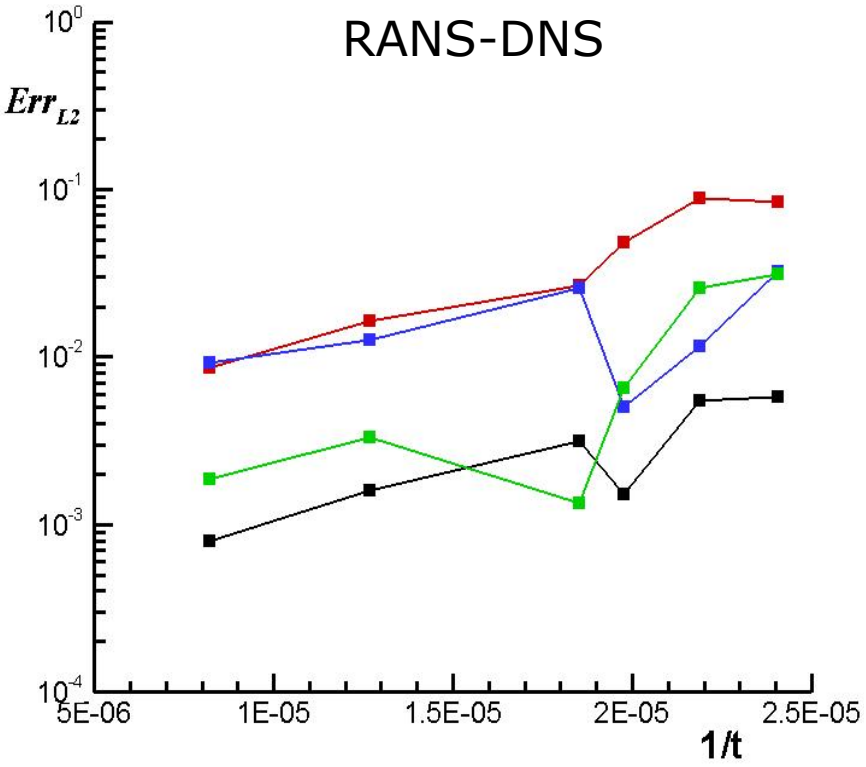
RANS-DNS convergence

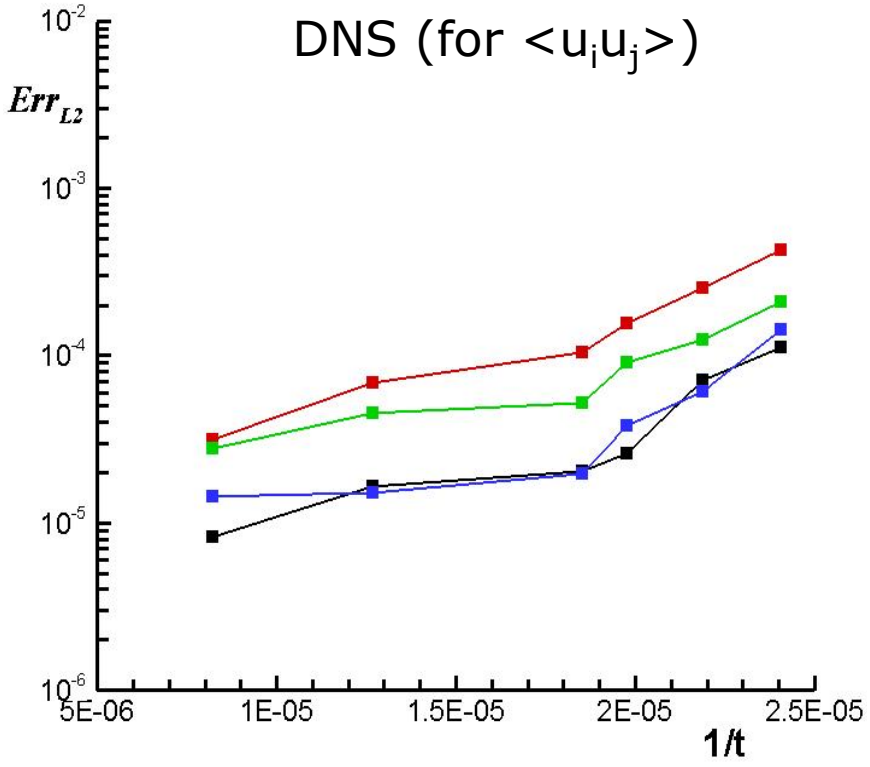


Error convergence

$< w^2 > < v^2 > < u^2 > < uv >$

$$Err_{L2} = ||f(t_n) - f(t_7)||$$

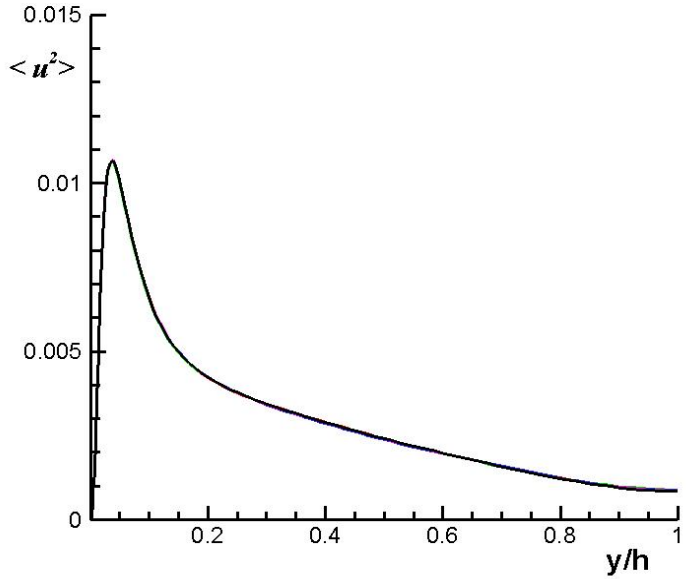


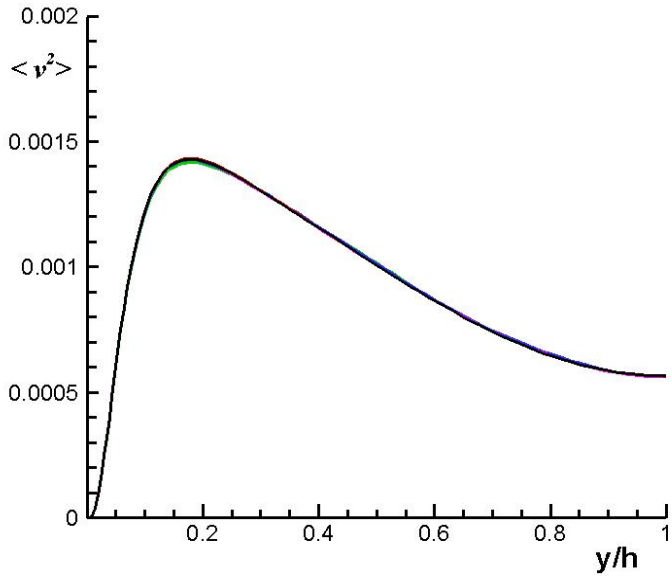


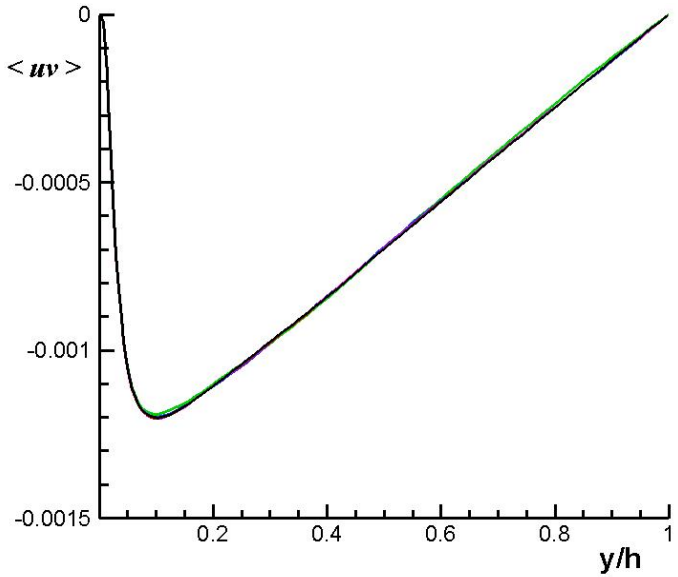
There is a systematic error in DNS and RANS-DNS data

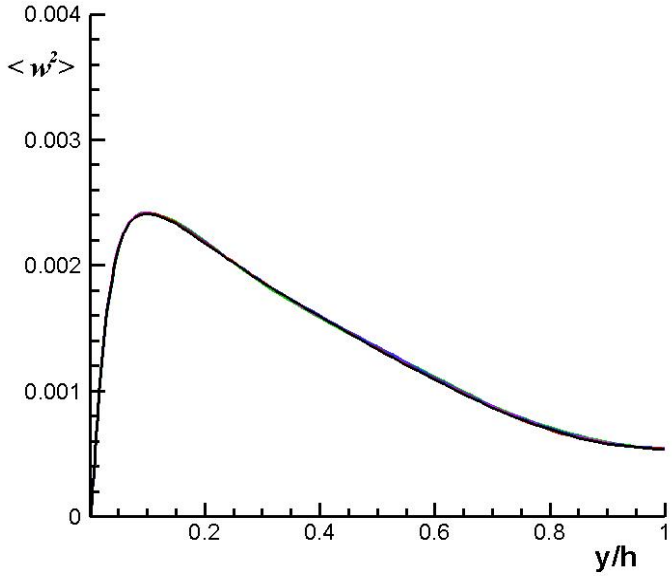
The systematic error is not obvious when the DNS profiles are plotted, instead of their errors (next slide).

DNS data convergence

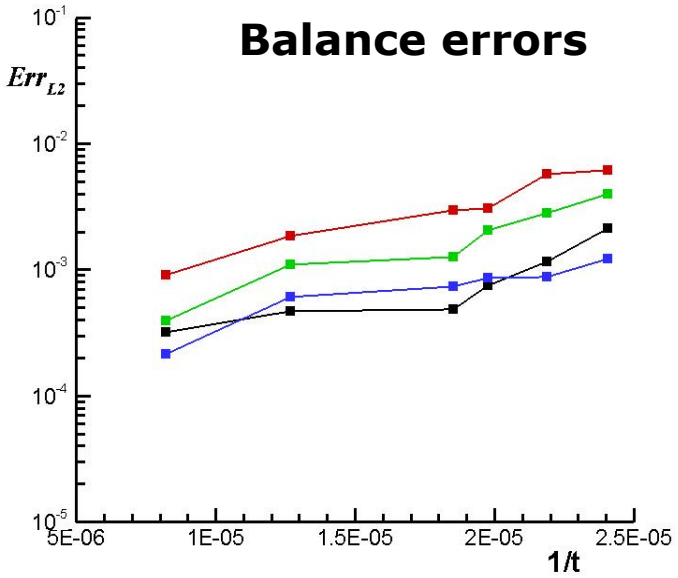


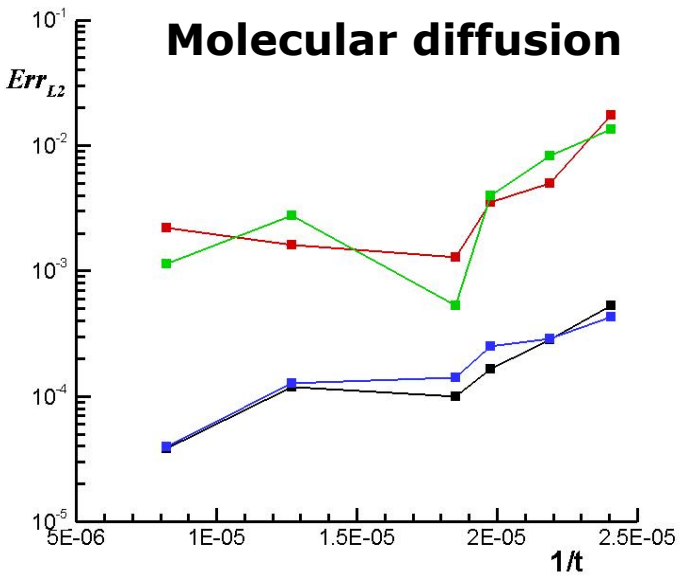


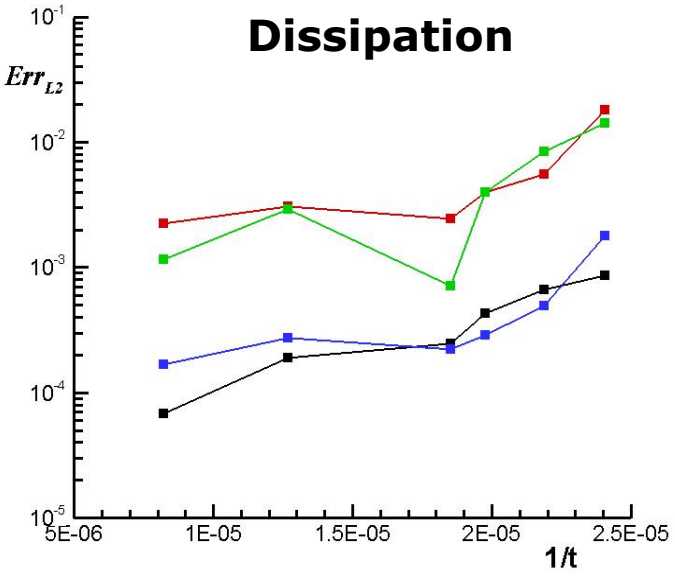


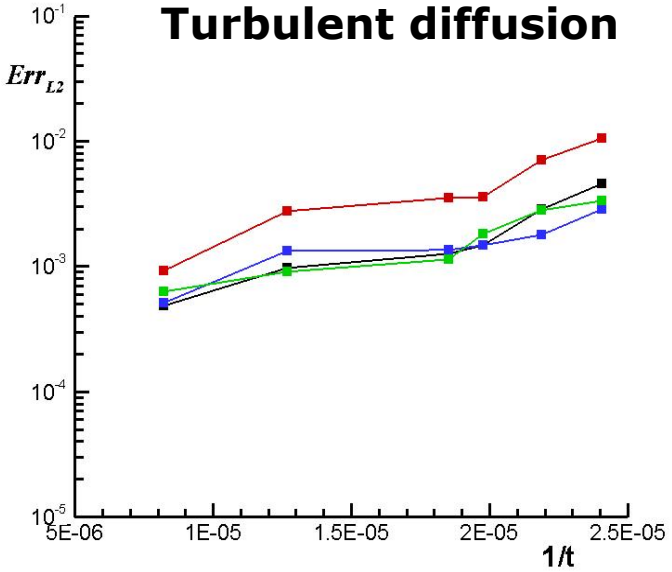


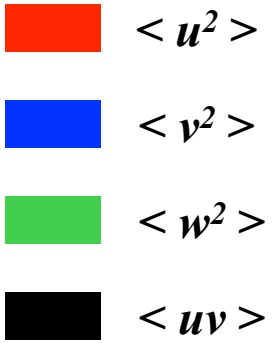
Error convergence for terms in the DNS budgets



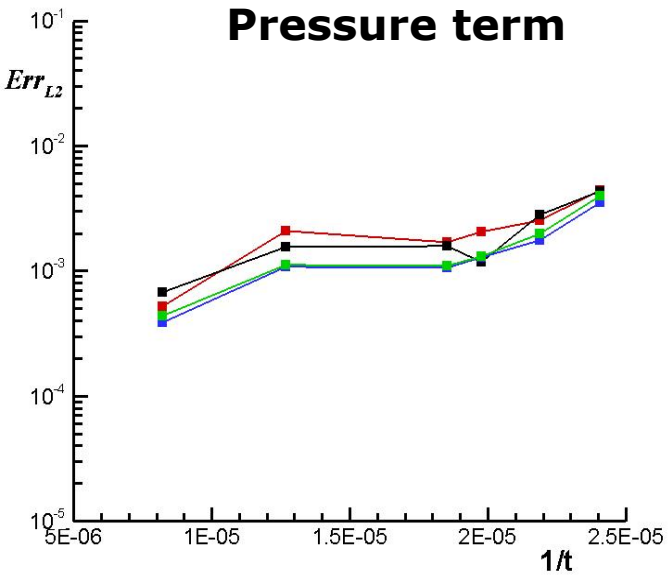


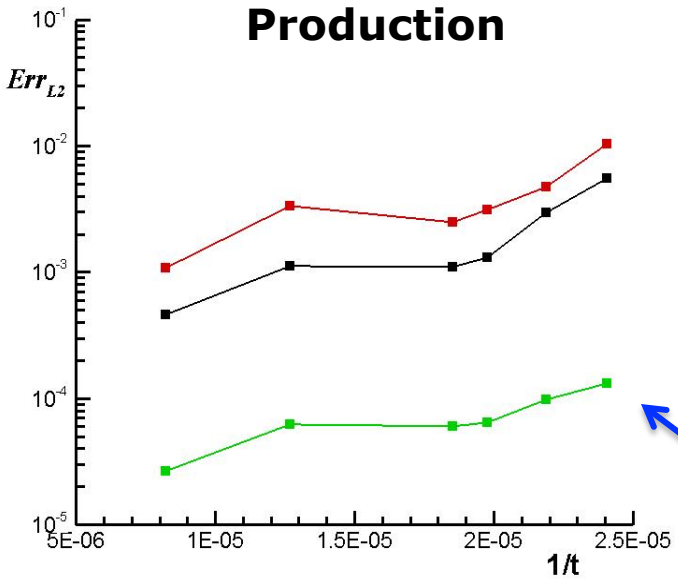






(Contd.)





$< u^2 >$

$< v^2 >$

$< w^2 >$

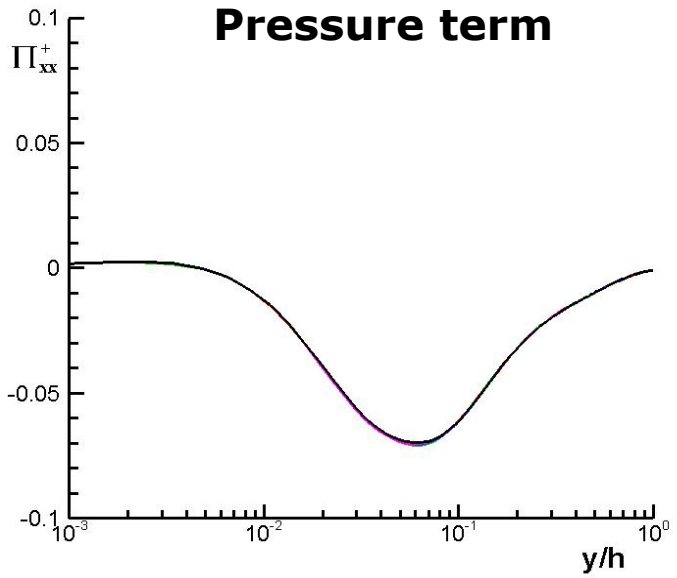
$< uv >$

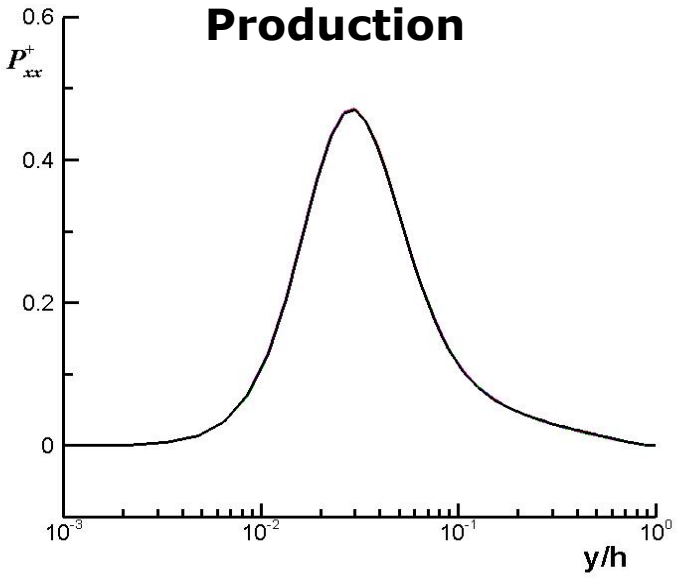
"zero" term

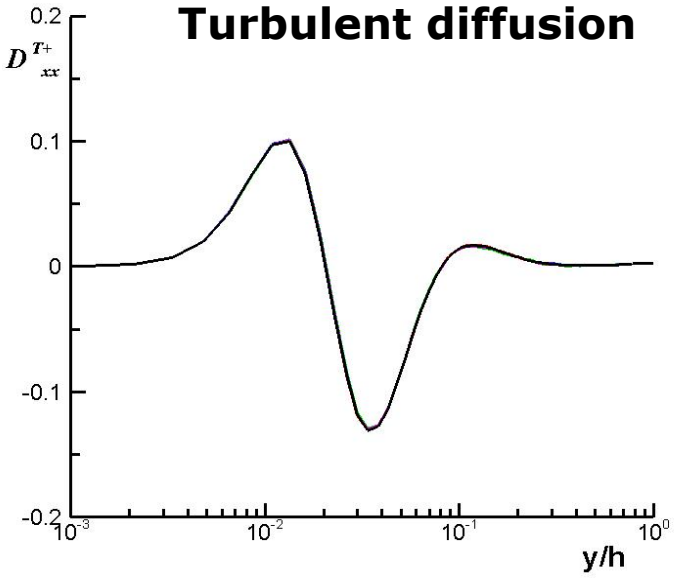
None of the terms converges in statistical sense.

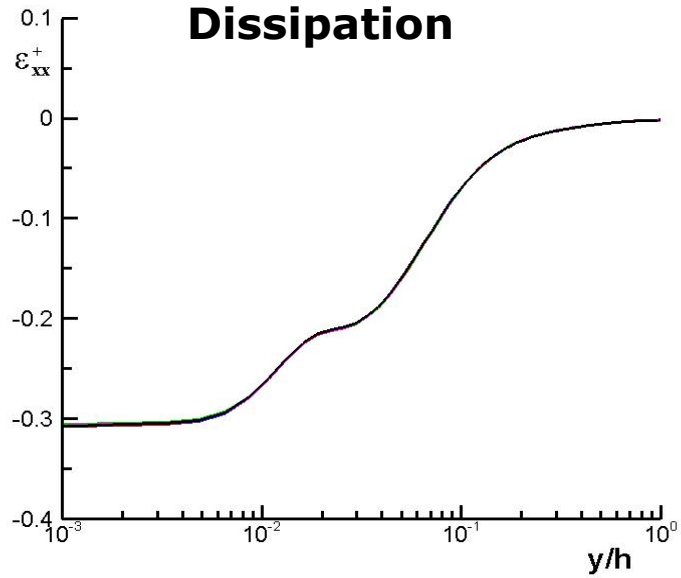
The systematic error is not obvious when their DNS profiles are plotted, instead of their errors (next slide).

Convergence of $< u^2 >$-budget terms

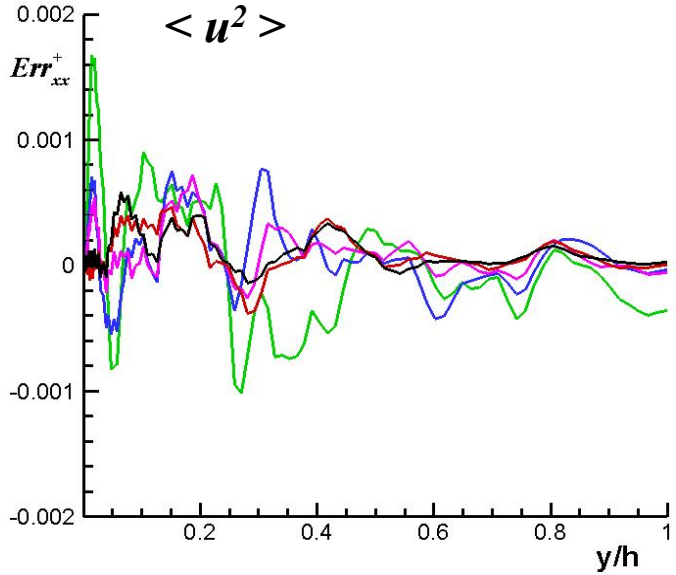


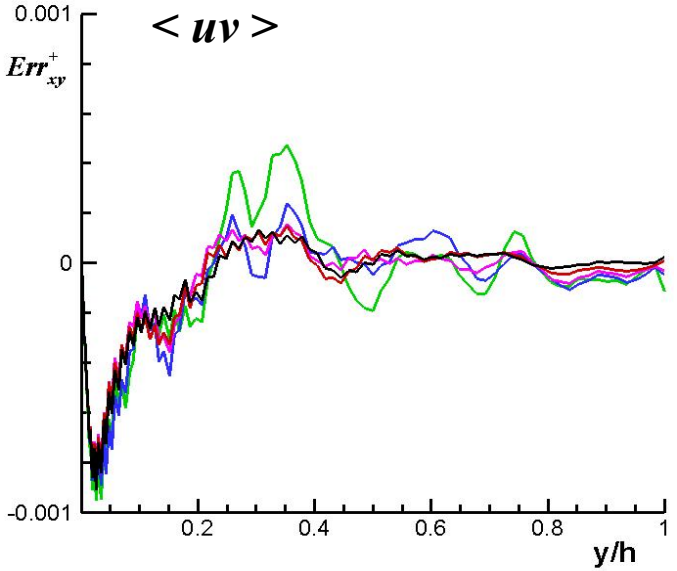


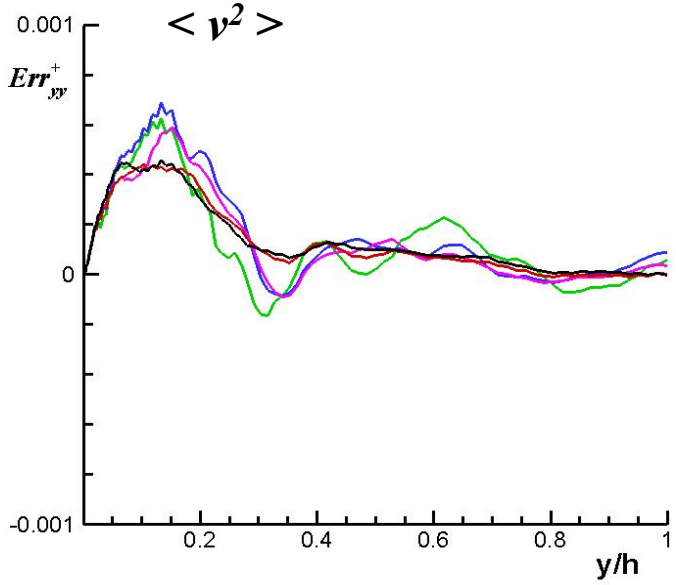


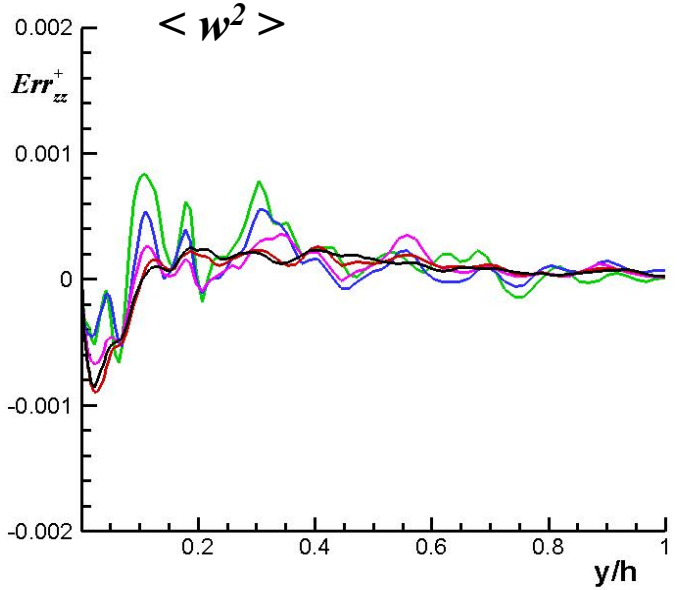


Balance error convergence









Summary

• The current balance errors are too high to compare with the molecular diffusion terms in all considered datasets except for very small Reynolds numbers. **This is a concern when using DNS data for model validation and model development (data-driven approaches) particularly near walls.**

• RANS-DNS simulations are rigorous, easy-to-implement framework for UQ in DNS data.

• DNS data (Reynolds stresses and terms in their budgets) do not converge in the statistical sense. **Running DNS longer does not seem to eliminate the systematic error present in the data.** The study has to be conducted with other solvers.

• The specific origin of the systematic error is currently unknown, but balance errors have a non-uniform distribution in the wall-normal direction, which may indicate an issue with the grid resolution.

Current

Test cases: mixing layer, channel flow **Solver:** Nek5000

in collaboration with Dr. Y. Peet (ASU)

NASA interests?

Compressible flow DNS, modeling, experiments

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AIAA TMBWG

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Dr. M. Rogers

Dr. C. Kiris

Dr. M. Olsen

Questions?

http://www.unm.edu/~poroseva/